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Flight Dynamics Analysis Branch End of Fiscal Year 2003 Report

Prepared by members of the Flight Dynamics Analysis Branch
Applied Engineering and Technology Directorate

Edited by C. Gramling, M. Houghton, O. Hsu, J. Lynch, D. Mangus, J. O'Donnell,
T. Stengle, and J. VanEepoel

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

February 2004

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Abstract

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 595, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2003. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including spacecraft navigation (autonomous and ground based); spacecraft trajectory design and maneuver planning; attitude analysis; attitude determination and sensor calibration; and attitude control subsystem (ACS) analysis and design. The FDAB currently provides support for missions and technology development projects involving NASA, other government agencies, academia, and private industry.

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1.0 Introduction

This is the fifth annual report produced by members of the Flight Dynamics Analysis Branch (FDAB) at the Goddard Space Flight Center (GSFC). The Branch is responsible for providing analytic expertise for trajectory and attitude systems. This includes dynamics and control analyses and simulations of space vehicles. The Branch creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization, orbit analysis, navigation, attitude determination, and controls analysis. The Branch also provides the expertise to support a wide range of flight dynamics services, such as spacecraft mission design, on-orbit sensor calibration, and launch/early orbit operations. An active technology development program is maintained, with special emphasis on developing new techniques and algorithms for autonomous orbit/attitude systems and advanced approaches for trajectory design. Specific areas of expertise resident in the FDAB are:

- Attitude and trajectory analysis and control design
- Control/structure interaction analysis
- Mission (attitude & trajectory) planning
- Estimation techniques
- Vehicle autonomy
- Constellation analysis
- Flight dynamics model development

Prior to this year, the FDAB was one of four branches in the Goddard Guidance, Navigation and Control Division (GNCD). In 2003, the Mission Engineering and Systems Analysis (MESA) Division (Code 590) was established by combining the GNCD and the Systems Engineering and Advanced Concepts Division. Goddard established this new division in order to improve its ability to design and develop complex missions of the future. The MESA division will be responsible for providing strong mission-enabling leadership for a broad range of advanced science missions. In addition, many planned future missions will rely on highly integrated observatories in which the spacecraft functions and performance cannot be separated from the instrument and science functions and performance. The MESA division now has the charter and the critical mass of people and skills to provide leadership in these areas. Although the role of the FDAB is generally the same, its closer alliance with mission system engineers should benefit the infusion of flight dynamics technologies into new mission concepts and improve the ability of the branch's mission designers to meet the needs of mission formulation study teams.

This document follows an outline similar to one used in past annual reports. It summarizes the major activities and accomplishments performed by the FDAB in support of flight projects and technology development initiatives in Fiscal Year (FY) 2003. The document is intended to serve as both an introduction to the type of support carried out by the FDAB, as well as a concise reference summarizing key analysis results and mission experience derived from the various mission support roles assumed over the past year.

The FDAB engineers that were involved in the various analysis activities within the Branch during FY2003 prepared this document. Where applicable, these staff members are identified and can be contacted for additional information on their respective projects.

2.0 Flight Project Support

This section summarizes FDAB support to GSFC flight projects during FY03. For purposes of this report, these projects are classified as:

- Development Missions: Approved missions under development.
- Operational Missions: Missions that were in-flight in FY03. This includes missions that were in the final stages of development and were successfully launched in FY03.

Support to future mission concept studies and proposal support for missions seeking project approval are covered in Section 3.

In FY02, a decision was made by NASA to not exercise the first option period for the Consolidated Space Operations Contract (CSOC). This contract provides space operations services including operation of the Goddard Flight Dynamics Facility (FDF). The FDF provides multi-mission flight dynamics operations services including:

- Orbit determination and product generation
- Attitude determination
- Maneuver planning
- Tracking data evaluation
- STS and ELV support (acquisition data generation)

Beginning January 1, 2004 the Mission Operations and Mission Services (MOMS) contract will replace CSOC. The MOMS contract will provide Goddard spacecraft services, including operations of the FDF and will also provide contractor resources necessary to support the FDAB in flight dynamics technology and development activities. As part of this change, the Goddard Flight Projects Directorate requested the FDAB to provide overall management responsibility for the FDF operations beginning in 2004. During FY03, the branch prepared for this transition by participating in the MOMS contract selection process and preparing statements of work for flight dynamics services that will be supported by the MOMS contract. Branch personnel also worked with the current CSOC FDF operations engineers to understand current operations.

To further prepare for FDF management responsibilities, the FDAB prepared a document entitled “Flight Dynamics Vision 2005.” This document summarized a vision for future flight dynamics operations at Goddard. This vision was developed by senior staff in the FDAB following a series of meetings to discuss future operations concepts and the transition of flight dynamics operations support to the MOMS contract. The FDAB management team recognized the need for this plan in order to guide the Branch through its planning for future flight dynamics operations and reengineering activities in the FDF. In many cases, this plan was based on the OPS2000 plan developed in 1995 and reinforced some of the ops concept elements presented in that plan.

2.1 Development Missions

2.1.1 Aquarius

Aquarius is a selected Code Y, Earth System Science Program (ESSP) mission that addresses NASA Earth Science Enterprise questions about the global cycle of water and the response of ocean circulation to climate change. Ocean salinity is the only surface parameter not currently measured from space. Aquarius will provide this measurement by monitoring global ocean radiometric emissions, which are influenced by surface salinity.

The primary science objectives of the mission are to measure global sea surface salinity, monitor freshwater cycling at the ocean surface, understand the response of ocean circulation to buoyancy forcing, assess the impact of buoyancy forcing on the ocean thermal feedback to the climate (e.g., El Niño prediction), and improve the ability to estimate the air-sea exchange of Carbon dioxide (CO2). The required mission duration is 3 years, with a goal of 5 years.

Over the past few years, the FDAB has provided a variety of analysis support for the Aquarius proposal team. The support included assisting in the tasks of orbit and launch vehicle selection; devising an orbit maintenance strategy; surface coverage analysis; and, evaluation of various sensor configurations. Analysis has also been performed to evaluate the design of the momentum management system, which resulted in a recommendation to increase the size of the magnetic torquer bars.

Aquarius is currently in the formulation phase, and recent work has focused on selecting a repeating, Sun-synchronous orbit that satisfies the data collection requirements of each instrument in the science payload. The orbit altitude is planned to be in the range of 590 to 650 km. Orbits with 9-day repeat cycles are being considered. Analysis is in progress to determine if these orbits will meet the global coverage requirement.

[Technical contacts: Frank Vaughn, Kristin Makovec]

2.1.2 Earth Observing System (EOS) Aura
http://eos-aura.gsfc.nasa.gov/

The Aura mission is planned for launch in early 2004 on a Delta 7920 rocket from the Western Test Range. The planned mission lifetime is six years. The Aura mission is composed of four complementary instruments: the High Resolution Dynamic Limb Sounder (HIRDLS), the Microwave Limb Sounder (MLS), the Ozone Monitoring Instrument (OMI), and the Tropospheric Emission Spectrometer (TES). Aura's major science objective is the study of the chemical interactions and climate change in the Earth's atmosphere, focusing on the upper troposphere and lower stratosphere. The Aura spacecraft (Figure 2-1) is 3-axis stabilized and will operate in a near-circular, Sun-synchronous polar orbit at an altitude of approximately 705 km, with ascending nodal crossings at approximately 1:45 PM mean-local-solar (MLS) time. Aura will fly in the "Afternoon Constellation" behind EOS Aqua (launched in May 2002) on an adjacent World Reference System path with a given offset such that the Aqua ground track will always intersect the Aura MLS field-of-view at the Earth's limb. Aura will follow Aqua with an along-track separation between 15 and 22 minutes. Figure 2-2 shows a schematic of how this is accomplished. In this example, Aqua is in an orbit with an ascending node mean local time (MLT) of 13:30; Aura will be in an orbit with MLT between 13:38 and 13:45.

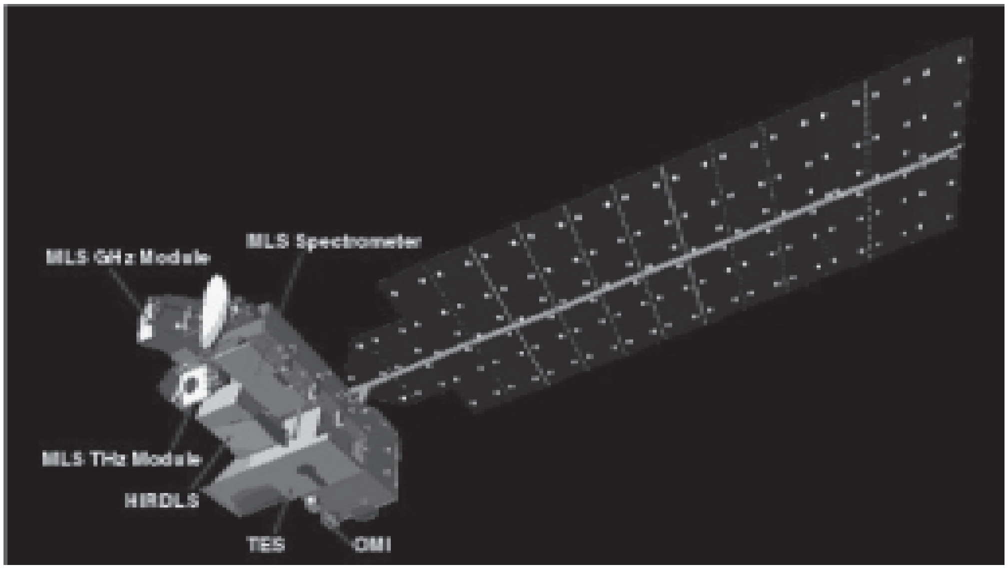

Figure 2-1. Aura Spacecraft (image courtesy of Aura Project Website)

During FY2003, the FDAB updated the ascent maneuver plan. The FDAB completed validation testing of the Commercial off-the-shelf (COTS) orbit determination (OD) system that was planned for incorporation into the Flight Dynamics System (FDS) in the Mission Operations Center (MOC). The decision was made not to incorporate the functionality at this time due to the immaturity of the end-to-end operations scripts/plans, so orbit determination (OD) will be performed using the same system that is operational for Aqua as provided by the Flight Dynamics Facility. The FDAB also presented flight dynamics material at the Aura Mission Operations Review (MOR), provided updates to the Mission Specific Requirements Document, refined specifications for products, and completed development of draft Interface Control Documents with the FDS external interfaces. The FDAB and supporting contractors performed acceptance testing of the Aura FDS and participated in various simulations, including FDS-internal simulations and external simulations with the Aura ground system and the flight operations team.

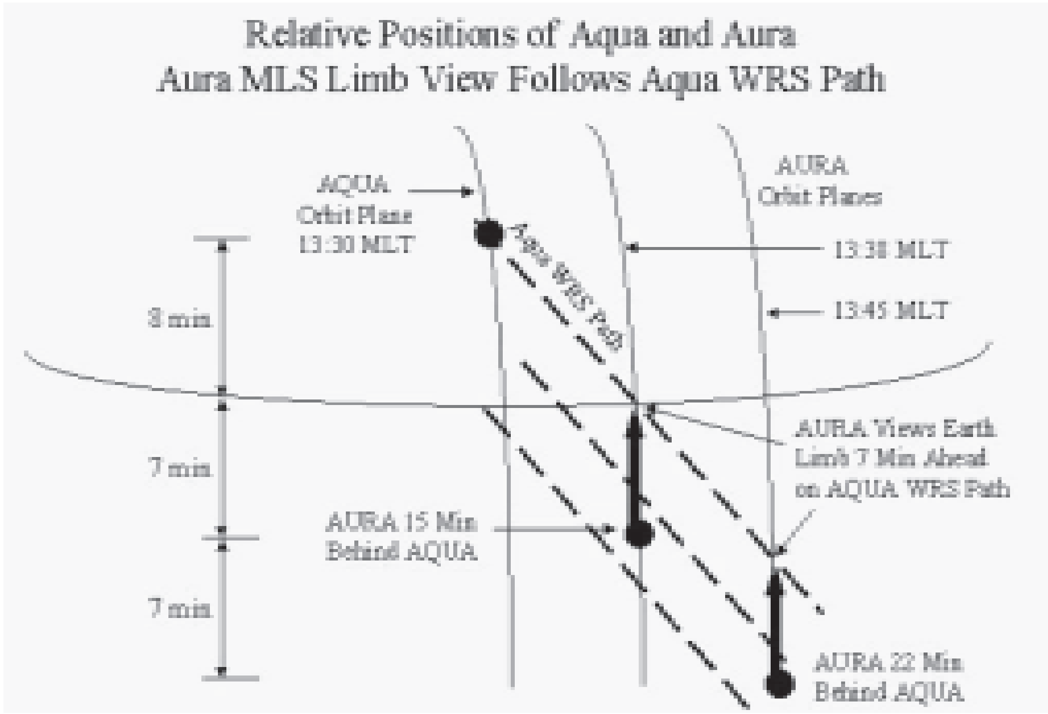

Figure 2-2. Aura & Aqua Flying in Constellation (Courtesy CSC/R. McIntosh)

[Technical contacts: Lauri Newman, David Tracewell]

2.1.3 EOS Constellation Coordination System (CCS)

A number of Earth Science missions have recently chosen to operate in similar orbits for the purpose of measuring phenomena at the same geographic or atmospheric location within a few seconds to minutes of one another. Known collectively as the "Afternoon Constellation" due to their afternoon ascending node-crossing times, the missions include Earth Observing System (EOS) Aqua, CloudSat, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), Parasol, EOS Aura, and the Orbiting Carbon Observatory (OCO) missions (Figure 2-3). The missions are owned and operated independently by several different agencies: Aqua and Aura by NASA GSFC, CloudSat and OCO by NASA Jet Propulsion Laboratory (JPL), and CALIPSO and Parasol by Centre National d'Etudes Spatiales (CNES).

In order to ensure the health and safety of the missions within the constellation, the Earth Science Mission Operations (ESMO) Office at GSFC is working with the Afternoon Constellation members to develop a documented process to facilitate information exchange between missions, to assess potential collision risk among the constellation members and to provide a resolution framework to be used in the event of contingencies. To facilitate this process, ESMO has tasked FDAB and the Mission Applications Branch (MAB), Code 583 to develop a tool called the Constellation Coordination System (CCS) that will receive orbit information from each mission in the constellation and determine collision risks. It also provides a communication conduit between the mission for sending data and messages and provides graphical monitoring of the health and safety of the mission for management review. The CCS is being built as an expansion of the capabilities of the Earth Science Collaborator tool built by MAB for ESMO. MAB is overseeing the development of the tool. FDAB is providing analysts to write specifications, perform constellation analysis, and perform acceptance testing of the system.

FDAB analysis for the constellation coordination effort includes evaluating the orbits of the member satellites for potential collisions and defining algorithms and specifications for the CCS software. They also help define the procedures for resolving conflict among member missions and provide input to the documentation of the interfaces between the CCS and the member missions. This year the task has supported two operations working group meetings, supported a System Design Review, and made several presentations to ESMO management regarding the capabilities of the CCS. There are 3 releases of the system planned for FY04.

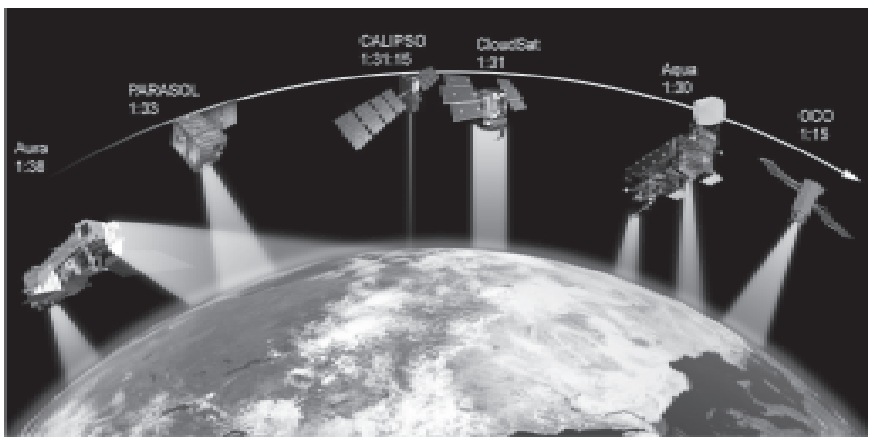

Figure 2-3. ESMO Afternoon Constellation (from 7/03 draft "Afternoon Constellation Operations Coordination Plan" by A. Kelly)

[Technical contact: Lauri Newman]

2.1.4 Gamma Ray Large Area Space Telescope (GLAST)

http://glast.gsfc.nasa.gov/

The Gamma-Ray Large Area Space Telescope (GLAST) is planned to launch in late 2006 on a Delta II launch vehicle from the Eastern Range. The nominal mission orbit is a 565-km circular orbit, inclined at 28.5°. Onboard navigation will be performed using a redundant pair of Global Positioning System (GPS) receivers.

FDAB personnel were asked to explore alternative orbit determination methods in the event of a GPS receiver failure. Since GLAST does not carry a transponder, the options are limited. FDAB recommended using a Differenced One-Way Doppler (DOWD) technique. This involves scheduling simultaneous one-way return link services through two Tracking Data Relay Satellite (TDRS) spacecraft and differencing the tracking data to remove the time-varying oscillator frequency bias. This approach will provide the best orbit accuracy with the least impact to the spacecraft and ground systems design.

FDAB personnel also provided several analysis items to the GLAST project. FDAB provided ground station and TDRS view periods to assist the project in developing their data acquisition strategy. Additionally, FDAB performed an orbital lifetime prediction that confirmed the lifetime analysis performed by Spectrum Astro; using the +2 sigma solar flux prediction, the expected lifetime exceeds 11 years. South Atlantic Anomaly (SAA) entry and exit profiles were also provided.

[Technical contact: Mark Woodard]

2.1.5 Geostationary Operational Environmental Satellite - N (GOES-N)

The GOES-N launch has slipped to at least the last quarter of 2004 or the first half of 2005. The FDAB provides consultation support during the launch and early orbit operations, but will play a larger role during post launch testing. In the pre-launch period and as consultants after launch, we try to stay prepared to help the Project with Flight Dynamics related anomalies or concerns. We have upgraded our software tools to make certain they are compatible with the GOES-N ascent plan. After the spacecraft is on-station, the FDAB will be involved with orbit determination and attitude dynamics support.

Currently, we are exploring a request from the Project's Mission Operations Support Team (MOST) to implement the capability to provide post-launch real time attitude information in the GOES Control Center. This effort would also provide a data stream to drive a graphical display of the spacecraft in the Satellite Tool Kit / Visualization Option (STK/VO) software. This software is particularly helpful in understanding attitude anomalies, such as going into safe-hold attitude control mode.

The FDAB GOES Team will participate in several planned testing programs for validating the GOES-(N-P) ground system. Work has already begun to familiarize FDAB personnel with the GOES ground system and to support test planning.

[Technical contact: Robert DeFazio]

2.1.6 Global Precipitation Measurement (GPM) Mission

http://gpm.gsfc.nasa.gov/

GPM is an international cooperative constellation of precipitation measuring satellites. Designed to measure the global 4-dimensional variability of rainfall, latent heating and the microphysics of the variability, data will be used to improve the prediction of climate change, weather, fresh water resources and severe storms. To satisfy this requirement in a cost-effective manner, the GPM project envisions using resources from already or soon-to-be launched satellites with suitable instruments (radiometers) for rainfall measurement. The program also aims to improve predictions of the Earth's climate, the weather, and some components of the global water cycle. This article will focus on the Flight Dynamics Analysis Branch's efforts in the areas of trajectory design, mission analysis and attitude control system design for the GPM primary spacecraft, which is to be built at GSFC.

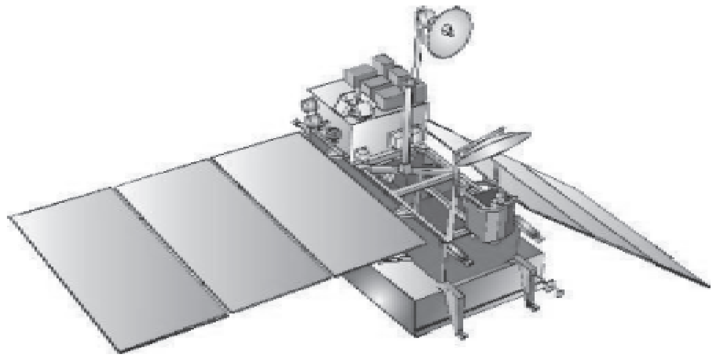

Figure 2-4. GPM Core Spacecraft Concept

The GPM-Core (Figure 2-4) is currently scheduled for launch in February 2009 in dual launch configuration with GCOM-A1 by an H2-A 202 Japanese launch vehicle. It has a required minimum lifetime of three years, with an expected lifetime of up to five years. The primary GPM spacecraft will be in a low-earth orbit with approximately a 400-km altitude and a 65-degree inclination. It is the baseline satellite for the GPM constellation ground calibration and it will also complement Earth coverage and precipitation measurement for the GPM data worldwide gathering concept.

Much of the navigation analysis effort in the past year has been determining an optimal approach to maintaining the GPM Core mission orbit and considering algorithms for performing it autonomously on-board with the AutoConTM flight software package. (See Section 4.3.7, *GPM Autonomous Orbit Maintenance* article in this document). Minimizing fuel usage as well as minimizing interruptions to science data collection while still conceiving a maneuver plan that is easily implemented were a few of the considerations that went into a 2-burn vs. 1-burn analysis of the orbit maintenance. Although both approaches, when optimized, appear to require similar Delta-V's, still more analysis is required to determine which might be more readily implemented on-board. While it is easier to maintain a circular orbit, thus minimizing altitude variation and requiring less calibration of the science data with a 2-burn approach, the 1-burn method requires fewer maneuvers. Therefore, there are fewer interruptions to the mission's primary objective of measuring precipitation. The ease of implementing the algorithms involved and the overall confidence in the solutions achieved by each will be the determining factor in the decision of which strategy to pursue.

Other types of navigation/mission analysis that the FDAB has performed over the past year for the GPM Project have been: optimization of the GPM constellation for science coverage; ground station coverage of the Core spacecraft during insertion, descent, and mission orbit; Tracking Data Relay Satellite System (TDRSS) coverage during those phases; control-box size trade space; mean elements comparison for the mission orbit; drag studies; and pointing error analysis.

Besides providing navigation support, the FDAB is responsible for attitude analysis support in designing the on-board attitude control subsystem (ACS) for the primary spacecraft. The previous year's support activities included the initial concepts culminating in the GPM Systems Concept Review (SCR) held in December 2002. From this initial concept the individual subsystems were tasked to begin in-depth trade studies to investigate different implementations that would meet the concept's intent. The ACS team's trade studies included reaction wheel and torquer bar sizing; thruster location and sizing; mode definitions and transitions; and a definition for safe hold. As with any mission in the early phases, the baselined spacecraft underwent several alterations to improve power and mass budgets. As a consequence of these alterations, the ACS team continuously provided analysis support as needed and provided updates to each trade study to ensure that, for each new spacecraft configuration, the ACS design would still meet requirements. At key points in the maturing concept design process, reviews were again held to verify the ACS concepts and designs. The MESA Division held a Concepts Peer review in March 2003 and the GPM Project office conducted a Delta Concept Review in May 2003.

As the concepts phase was maturing, the GPM ACS entered a preliminary design phase to define the requirements and implementation of the onboard flight software. The initial efforts during the preliminary design phase were spent to define the modes, sensor configurations and mode transitions in more detail. The output of this effort will go into the requirements for developing the ACS high fidelity (HiFi) dynamics simulator. This Hifi simulator will be the means to test control algorithms and logic before it is translated to the final onboard software. The HiFi simulator will be developed using the Mathworks Matlab/Simulink technical computing software tools. The development effort will also try to incorporate reusable flight software C-code where possible, and where Simulink models are used, to translate them into C-code using the Mathworks autocoding tools. Because GPM and the Solar Dynamics Observatory (SDO) missions are occurring at roughly the same time, efforts are being made to have commonality in models and naming conventions for the HiFi simulators and flight software. This will make the development and testing of onboard flight software more efficient and more reusable for future missions. The next major event in the design phase is the completion of the rigid body analysis for all defined modes, culminating in a Preliminary Design Review (PDR) currently scheduled for the summer of 2004.

[Technical contacts: Joseph Garrick, Chad Mendelsohn, David Folta]

2.1.7 InFocus

Infocus (International Focusing Optics Collaboration for μCrab Sensitivity) is a nine-meter focal length X-ray telescope with revolutionary focusing optics and detectors that are a precursor for Constellation X. The telescope is to be flown on stratospheric balloons at 40 km altitude observing extragalactic targets for extended periods of time. The Flight Dynamics Analysis Branch provides ongoing support for dynamics and control analyses of the telescope pointing system. In prior years it supported the integration, test, and field launch operations of two InFocus flights: a detector test flight in August 2000, and a first flight of the telescope in July 2001. This year, design analysis has been provided for a second telescope mission scheduled to launch in the spring of 2004 at Fort Sumner, New Mexico. This work has focused on revisions of the pointing system configuration from the 2001 flight which include:

1. Development of a cross elevation control loop.
2. Incorporation of multi-star tracking star camera (ST5000 Mach 2) into the control loops
3. Addition of GPS for attitude determination into the control loops
4. A faster and more powerful pointing system Central Processing Unit (CPU)
5. Completely revised pointing software written in C

Major Branch support has been provided for the cross elevation control loop, the star camera, and the revised pointing software. Also, ongoing analyses to better understand and characterize the attitude dynamics from the balloon load-train (parachute and cable ladder) gondola has continued. These are based on studies of the gyro, GPS, and magnetometer flight data returned from both flights along with use of high-level dynamics modeling tools.

These revisions are necessary because the original telescope pointing system, an adaptation of an older system used for a smaller telescope with 0.5 degree pointing accuracy requirement, did not meet the InFocus requirement for three-arcminute telescope pointing accuracy on the 2001 flight. This occurred because higher-than-expected winds at float altitude overpowered the azimuth/elevation pointing system. Preflight testing by suspension of the entire gondola from a ceiling crane did not reveal the effects of stochastic high winds propagating down a 250 ft long load train on cross axis motion. Although high wind effects might be avoided by restricting balloon launches to the spring and fall periods when upper atmospheric winds statistically pass through zero, one cannot be certain they will not reoccur.

The azimuth and elevation loops cannot remove swinging motions about the gondola's remaining axis, cross elevation. Cross elevation swing motion, while the telescope was pointed to high elevation targets, was the largest contributor to pointing error on the second flight. Several approaches to eliminate this motion were analyzed and it was concluded that the best approach would be to cancel the gondola rotation by actively tilting the gondola platform. A method for doing this is now being analyzed, which employs a special mechanism to make differential adjustments of the lengths of the straps that attach the gondola to the cable ladder.

The flight will carry a star camera, capable of multi star tracking and identification, and a PIVOT GPS receiver with attitude determination capability. Both sensors will be integrated into the onboard control loop to enhance the previous approach where an operator on the ground had commanded azimuth and elevation corrections after viewing down-linked star camera images; on the 2001 flight the corrections could not be determined due to the cross elevation swinging and low image transmission rate. During the day, GPS serves as the primary sensor. At night, the GPS is the primary sensor with the star camera providing augmented data. Alignment of the GPS and star camera with the telescope bore sight will be a crucial process during integration and test.

The incorporation of new software written in C replaces assembly level code used on the older system and allows comparatively rapid software revisions for dynamics and control problems arising in the integration and test phase. It is also possible to incorporate a Kalman filter to improve the attitude determination from all sensors.

Finally, analysis is being done to model and define the alignment procedures and requirements of the various sensors and the telescope optical axes.

[Technical contacts: David Olney, Keith DeWeese]

2.1.8 James Webb Space Telescope (JWST)

http://www.jwst.nasa.gov/

JWST has a planned launch in 2011 into a Sun-Earth L2 libration point orbit. The JWST spacecraft has a rather unique design (see Figure 2-5 for deployed configuration). The delicate optics of the telescope requires protection from direct sunlight. When deployed, a large 200 m^2 sunshield separates the science instruments from the spacecraft bus. The spacecraft bus, therefore, is always on the sunward side of the sunshield. All thrusters are on the spacecraft bus pointed generally in the sun direction. JWST has a limited 68 degree pitch range and a 5 degree roll range in order to keep the telescope shielded from the sun.

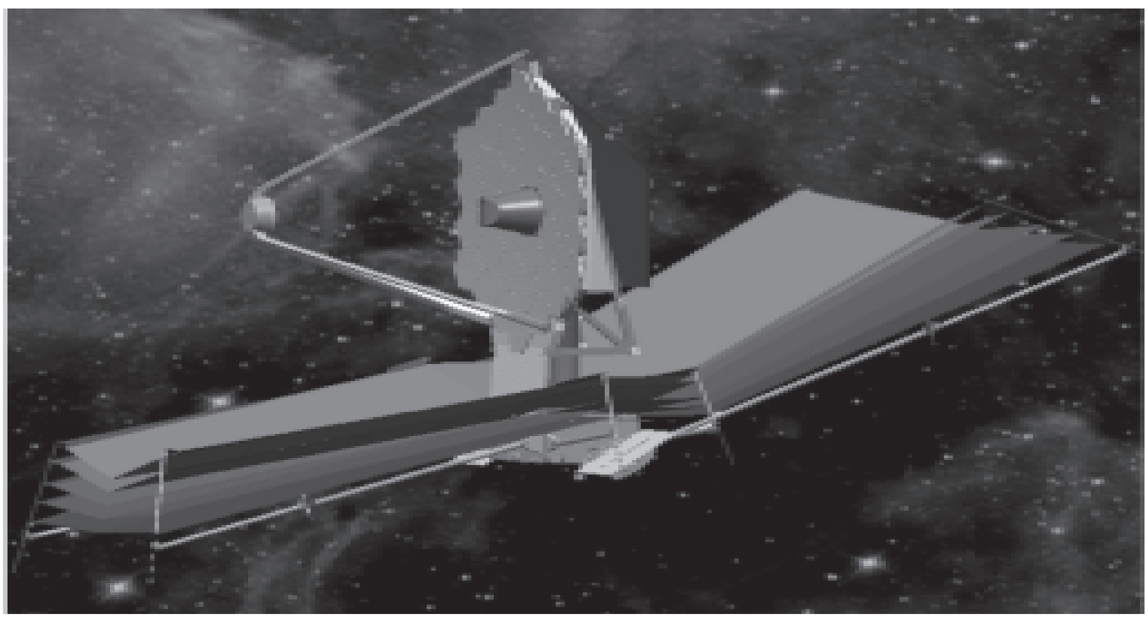

Figure 2-5. Northrop Grumman Space Technology JWST Design (Courtesy of NGST)

JWST presents several unique flight dynamics problems. Because of the unbalanced orientation of the thrusters, the delta-H (change in momentum) maneuver is not a zero delta-V (change in velocity) maneuver. Perturbations from the momentum unloads will affect orbit determination and station-keeping.

The FDAB has performed studies to minimize the affect of momentum unloading and to optimize the station-keeping delta-V costs. These studies have led to the following changes in the original NGST design:

- The shape of the sun shield has been redesigned to reduce solar torque.
- The spacecraft orientation will be optimized prior to each momentum unload.
- The science community has agreed to a rewriting of requirements, which should present no limitations on science targets, but allow the design to meet mission lifetime requirements.

The FDAB also supported analysis that led to the selection of the Ariane 5 ECA launch vehicle. FDAB personnel traveled to Envy, France for a technical exchange on JWST requirements and interface issues.

The optimization of spacecraft attitude analysis was performed to assess the station-keeping delta-V budget required for JWST, under the presence of frequent momentum unloads. The direction of the resultant delta-V from a momentum unload is dependent on the direction of the momentum vector in the body frame. In turn, the momentum vector is a function of the science targets. The science targets are chosen with a short lead time and onboard algorithms will optimize observatory efficiency real-time if targets are missed. Thus, the science target schedule is dynamic and unpredictable, and the direction of the momentum unload resultant delta-V is unknown.

This analysis looked at all possible directions for the resultant delta-Vs and performed station-keeping maneuvers to correct the trajectory every 22 days. This was the maximum frequency allowed for station-keeping maneuvers so that accurate orbit determination could be performed between each station-keeping maneuver. The total lifetime station-keeping delta-Vs are shown as a contour plot in Figure 2-6 as a function of resultant delta-V direction. The direction of the resultant delta-V is shown as an angle in the ecliptic plane and an angle out of the ecliptic plane. Momentum unloads were performed every four days with a resultant delta-V of 8 mm/sec.

The analysis shows a clear region of resultant delta-V directions that would require very high station-keeping delta-V to correct – up to 125 m/sec for the 10-yr mission. The direction is generally along the Rotating Libration Point (RLP) +*X* axis, 20 degrees towards +*Y*. The analysis also shows regions near the Ecliptic poles and towards RLP - *Y* that require very little station-keeping delta-V. Without knowledge of the direction of the momentum vector, a worst case assumption would have to be made and the station-keeping delta-V set at 125 m/sec.

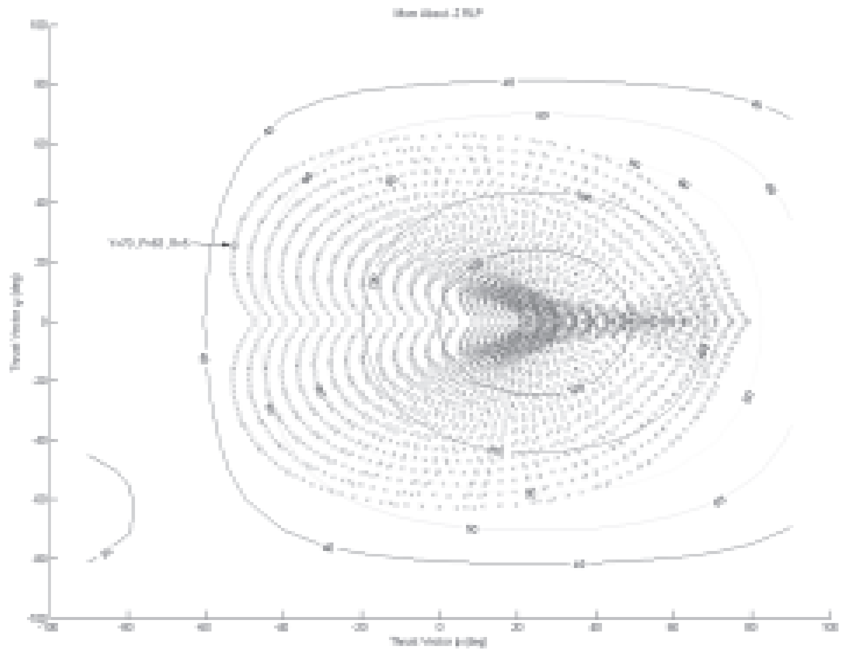

Figure 2-6. Resultant Delta-V Directions for JWST Attitudes within the FOR

Given the sensitivity to resultant delta-V direction, a reorientation of the spacecraft prior to every momentum unload might improve the station-keeping delta-V budget. Assuming the spacecraft could reorient to any attitude within its field of regard (FOR), analysis was performed to assess the resultant delta-V vector for all spacecraft attitudes. The optimum attitude was then selected for that momentum vector based upon minimizing the station-keeping delta-V. An example is shown in Figure 2-6, where the momentum vector is assumed be to in RLP -*Z*. The X's indicate resultant delta-V directions for various spacecraft attitudes within the FOR. The minimum station-keeping delta-V point is marked with an O. The spacecraft attitude required to achieve that resultant delta-V, from unloading momentum about RLP -*Z*, is shown as spacecraft yaw, pitch and roll angles (in degrees). In this example, the very low cost regions of station-keeping delta-V cannot be reached by any spacecraft attitude. However, given this momentum vector, a station-keeping delta-V can be achieved that is significantly lower than the maximum station-keeping delta-V for any resultant delta-V direction.

The results for all momentum vector directions are shown in Figure 2-7. The worst case momentum vector direction is the RLP -*Z* axis. Even with this worst case momentum vector direction, a reorientation of the spacecraft within its FOR will reduce the station-keeping delta-V budget to only 50 m/sec for a 10-yr mission. This is a 60% improvement over assuming the worst case resultant delta-V direction and not reorienting the spacecraft.

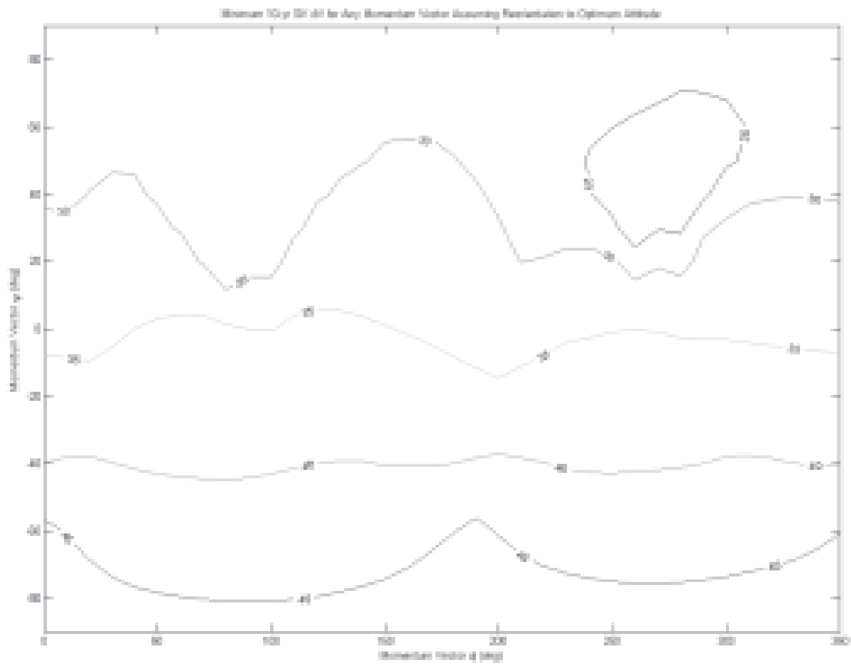

Figure 2-7. Minimum JWST Station Keeping Delta-V for Different MomentumVectors

JWST is manifested for launch on an Ariane 5 ECA launch vehicle. Mass limitations require a limit of 469 kg of fuel onboard. Given the launch vehicle correction errors, the momentum unloading requirements, and the launch window constraints, the reorientation is required in order to meet the stated fuel mass requirement.

[Technical contacts: Mark Beckman, David Folta]

2.1.9 Magnetospheric Multiscale (MMS) Mission

http://stp.gsfc.nasa.gov/missions/mms/mms.htm

MMS is part of the Sun-Earth Connection program, one of the four principal science themes of NASA's Office of Space Science. The major focus of the Sun-Earth Connection program is investigating the physical processes that link the Sun and the Earth. MMS is a four-spacecraft solar-terrestrial probe designed to study magnetic reconnection, charged particle acceleration, and turbulence in the key boundary regions of the Earth's magnetosphere. An Announcement of Opportunity for the instrument complement and principle investigator teams was released in January 2003. Two proposal teams responded, and in September 2003 both teams were selected for further refinement of their mission concept. Final selection of one team is expected in September 2004. More details about the mission can be found at the web site provided above.

Mission Design

The MMS mission consists of four science phases. The first two phases are low inclination, highly eccentric orbits, with apogee at 12 Earth radii during Phase One and at 30 Earth radii for Phase Two. Relative separations among the four spacecraft can be as close as 10 km. Earlier efforts concentrated on identifying characteristics of these orbits.

The third phase involves using two lunar flybys to change the orbit inclination to one suitable for the fourth phase, which is a 10 by 50 Earth radii orbit inclined 90 degrees to the ecliptic. Recent work has produced an automated method for finding flyby trajectories, greatly reducing the time required to find such trajectories. This method allows more candidate trajectories to be examined than previously possible. Other recent work has produced a method for finding the best trajectories that achieve a tetrahedral configuration commensurate with the mission science goals. Additional work has produced an optimization method that designs trajectory maneuvers for maintaining and resizing the tetrahedron formed by the four spacecraft. Results from these analyses are available in five technical papers, given at the 13th American Astronautical Society (AAS)/American Institute of Aeronautics and Astronautics (AIAA) Space Flight Mechanics Meeting, the 2003 Flight Mechanics Symposium, and the Third International Workshop on Satellite Constellations and Formation Flying.

MMS Orbit Determination Analysis

The GPS Enhanced Onboard Navigation System (GEONS) relative navigation simulations for the MMS Phase 1 1.2x12 Earth radii orbit tetrahedral formation demonstrated that science objectives of 100 km absolute position and 1% of the separation (100 m near apogee) relative position accuracy can be met using any of three options: two-way ground station Doppler and crosslink measurements processed on the ground, GPS for all satellites with or without crosslink, or GPS for local and crosslink from all remote satellites. The latter two options are significantly more accurate, and could be implemented onboard, potentially leading to operational cost savings. The crosslink measurements significantly reduce relative navigation errors. These results were presented in greater detail at the 2003 Flight Mechanics Symposium (October, 2003).

[Technical contacts: Russell Carpenter, Cheryl Gramling, Michael Moreau, Charles Petruzzo]

2.1.10 Solar Dynamics Observatory (SDO)

http://sdo.gsfc.nasa.gov/

The Solar Dynamics Observatory (SDO) has moved from Phase A to Phase B in the past year. There have been many project and subsystem level reviews supported by the engineers in Code 595. The Mission Definition Review was held in December 2002. The spacecraft Requirements Review was held in February 2003. The Spacecraft Concept Review was held in April 2003, and the Guidance, Navigation and Control (GNC) Subsystem Peer Review was held in July 2003. Much of the work done for the attitude area of the GNC subsystem has been in requirements definitions, trade studies, interfaces with other subsystems, and interfaces between the parts within the GNC subsystem.

For the Flight Dynamics team, the reporting period was largely a requirements phase. Level 2 project requirements were prepared in the *Mission Design Requirements (MDR)* phase. Level 3 Ground System requirements were developed in the *Detailed Mission Requirements (DMR)* phase. Finally, Level 4 requirements for selecting and modifying software were developed for flight dynamics support.

The SDO mission profile fluctuated due to numerous increases in spacecraft separation mass. Potential launch vehicles also changed from a Delta-II to possibly a Delta-4 or Atlas-5. The Flight Dynamics team supported a series of parametric studies of mission profiles to aid in analyzing spacecraft design changes. This was most notable in the area of propulsion system design where the number and size of thrusters was the subject of a large trade study with propulsion and attitude.

Additional mission analysis studies were performed in the areas of high gain antenna visibility, omni antenna placement and coverage, momentum management operational concepts, station keeping operations, and orbit determination error analysis.

Requirements for beginning the design and implementation of the SDO Flight Dynamics System (FDS) progressed with a System Requirements Review held in late September. In preparation for the System Requirements Review (SRR), the Flight Dynamics team contributed to the DMR and an operations concepts document and wrote the FDS requirements document.

Prototyping work was initiated with contractor help on software to model the SDO bipropellant maneuver planning and calibration system. An early test case using GOES-L data showed promising results. Other commercial off-the-shelf (COTS) and institutional software has been reviewed with initial recommendations made for meeting the FDS functional requirements. The Project Preliminary Design Review (PDR) is scheduled for January 2004. The SDO FDS design is reasonably well understood because it will rely heavily on heritage software and proven operational procedures.

Trade studies for reaction wheel size and location were performed many times during the year, based on models developed for the Solar Pressure and Aerodynamic Drag (SPAD) software. The SPAD results were used with an in-house software package to calculate wheel parameters for all phases of the missions. In addition, we received reaction wheel induced vibration data from two wheel manufacturers, and this was used to perform some detailed jitter analysis. We also received a preliminary finite element model from the mechanical team that was used in this analysis. This is the earliest a finite element model has been received from the mechanical team, and it helped to eliminate fears about meeting tight jitter requirements.

The ACS analysis team has also been creating low-fidelity (LoFi) simulations of the various control modes. Every mode has been simulated, and some of the simulations have been used in trade studies for Safehold Mode and for the thruster control modes. In addition, rigid body linear analysis has been performed to provide control gains for the simulations. A high-fidelity (HiFi) simulation is starting to be developed, and as part of that effort, we've done some analysis on using Matlab's Real Time Workshop toolbox to generate flight software for SDO. This has involved close work with the Flight Software Branch (Code 582) to determine the scope, applicability, and requirements for generating code.

[Technical contacts: Stephen Andrews, Robert DeFazio, Rivers Lamb]

2.1.11 Space Technology 5 (ST-5)

http://st5.gsfc.nasa.gov/

Space Technology 5 (ST-5) is a mission in the New Millennium Program and NASA's first experiment in the design of miniaturized satellite constellations. The mission will last 3 months. During this time the constellation of three spin-stabilized spacecraft will validate new technology for spaceflight. These technologies include a miniature cold gas thruster, X-band transponder, flexible interconnects, variable-emissivity coatings, ultra low-power logic, and autonomous constellation management ground software, as well as various technology improvements embedded in the spacecraft itself. In addition to validating these new technologies and instruments, the mission goal is to reduce the weight, size and cost of space missions, while preserving or improving technical capabilities.

The ST-5 GN&C team is conducting studies for the maneuver sequence to validate on board thrusters. The formation goal is to achieve a 0.5 hour Mean Local Time (MLT) separation between spacecraft in a string of pearls fashion. Given the limited on board propulsive resources, the deployment of the three spacecraft to achieve a goal of 0.5 hour MLT must be designed to be as efficient as possible. Furthermore, as a launch vehicle selection for ST-5 continues and the launch parameters remain unknown, designing a constellation scheme robust to unknown orbital parameters and meeting operational constraints is crucial for mission success.

ST-5 team member Anne DeLion completed her Professional Intern Program (PIP) Level II requirements with an investigation into the feasibility of using ballistic properties to perform formation control. Results of this study show formation station-keeping is not viable for the current strawman orbit, but with lower orbital altitudes and lower eccentricities, the feasibility increases.

ST-5 team member Rivers Lamb joined the team at the end of the summer and has begun his PIP Level I project on a characterization of post maneuver relative dynamics of the ST-5 formation in support of preliminary release and maneuver planning for any desired initial orbit.

The onboard ACS hardware consists of a Sun sensor mounted perpendicular to the spin axis, a three-axis magnetometer, and a single cold gas thruster. The challenge was to provide an ACS that uses simple algorithms to minimize onboard processing and work with the limited sensor and actuator compliment. Algorithms developed for the ST-5 ACS use rhumb line precession to keep the spacecraft spin axis aligned with the ecliptic pole and to reorient the spin axis when orbit adjust maneuvers are required. These algorithms have been tested using a high-fidelity simulation that models the spacecraft orbital and rotational dynamics, sensors, actuators, and space environment. Passive nutation damping will be achieved using a fluid-filled ring damper. In the past, fluid-filled ring dampers have required a fluid reservoir to reduce the internal pressure of the damper that increases as the fluid expands with increasing temperature. The small size of the ST-5 spacecraft has allowed a smaller fluid-filled ring damper to be designed that does not require a fluid reservoir and functions at internal pressures up to 10,000 psi. This provides simpler design, integration, testing and lower weight. The damper will be tested at NASA/GSFC by mounting the damper on the platform of a torsional pendulum and observing the damping of the platform rotational motion with rates telemetered via an radio frequency (RF) link.

FDAB personnel used the General Maneuver Program (GMAN) to model the ST-5 rhumb line precession maneuver. The results compared favorably to the algorithms developed by James Morrissey of the GN&C Systems Engineering Branch, thereby validating the algorithms for mission operations.

[Technical contacts: Marco Concha, Mark Woodard]

2.1.12 Space Technology 7 (ST-7) Disturbance Reduction System (DRS)

The Space Technology 7 (ST-7) Disturbance Reduction System (DRS) is a project within the New Millennium Program with a mission objective to test two advanced technologies: a Gravitational Reference Sensor (GRS) and micro-Newton colloidal thrusters. ST-7 is scheduled to fly as an instrument package aboard the European Space Agency's (ESA's) SMART-2, the Laser Interferometer Space Antenna (LISA) pathfinder spacecraft, in 2007, which is on a drift-away trajectory towards the Sun-Earth L1 Lagrange point. Some of the technical objectives of this mission are to validate that a test mass can be made to follow a trajectory determined by gravitational forces within $3x10^{-14}$ x $(1+(f/3\ mHz)^2)\ m/(s^2\sqrt{Hz})$, and validate spacecraft position control to an accuracy of less than 10 $nm/\sqrt{Hz}$ within the measurement band of 1-30 mHz. ST-7 is a joint venture between the Jet Propulsion Laboratory, Stanford University, Busek Co., Inc., and NASA Goddard Space Flight Center (GSFC). The responsibilities of GSFC's Flight Dynamics Analysis Branch (FDAB) include the development of the Dynamics Control System (DCS) that controls the spacecraft position and attitude to establish drag-free motion of the test masses within the GRS units, development of a full nonlinear dynamic model of the spacecraft and test masses (high-fidelity simulation model), and generation of flight code for the DCS. In addition, the FDAB has been studying possible thruster configurations and their impact on mission objectives.

ST-7 consists of two GRSs with internal free-floating cubic test masses designed to follow gravitational trajectories and two clusters of four thrusters for spacecraft translational and rotational control. The DCS is responsible for using star tracker data and GRS data to generate commands for the thrusters, and the commands are DCS mode dependent. Five operational modes exist within the DCS: attitude-only mode, accelerometer mode, initial drag-free mode, interim drag-free mode, and full-drag free or science mode. In the science mode, the DCS centers the spacecraft in translation about the reference test mass and centers the spacecraft in the transverse axis about the non-reference test mass using spacecraft rotation in the measurement band. Control for the test mass' relative attitude and non-reference test mass position in the sensitive axis is provided by the GRS suspension loop. A representation of the ST7 mission is shown in Figure 2-8.

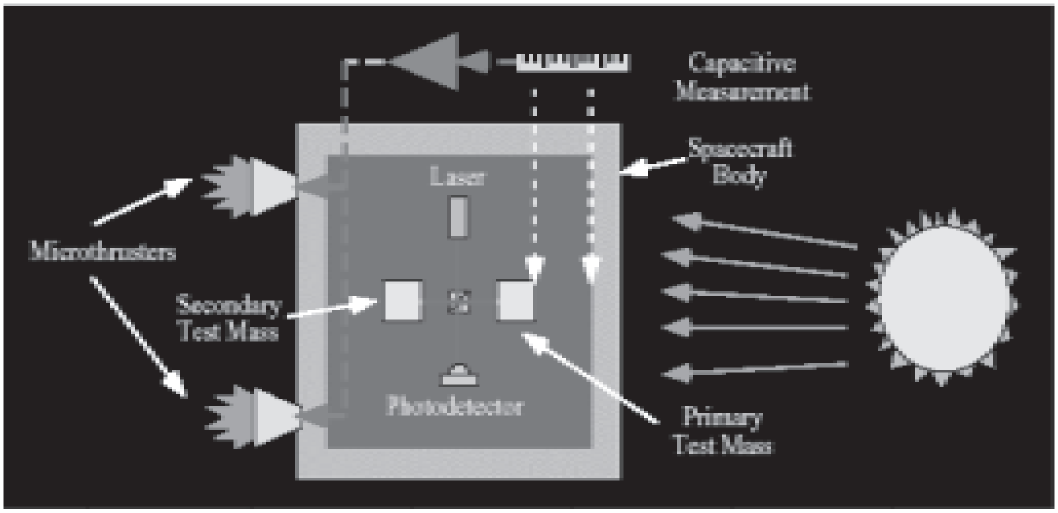

Figure 2-8. ST-7 Mission Representation

During FY 2003, the FDAB accomplishments included:

- Completion of the preliminary design of the controllers for all five DCS operational modes. The controllers were validated and they met all performance and stability goals and an example is shown in Figure 2-9. The figure shows the root power spectral density (PSD) for the relative X-position of Test Mass 1 and that the requirements are met within the measurement band.
- Development of a nonlinear 18-Degree of Freedom (DOF) simulation, including three translational and three rotational degrees of freedom for the spacecraft and test masses, used for controller validation in terms of stability and performance predictions. This simulation will be used in mode transition analysis.
- Thruster configuration study that investigated the effects of the configuration on maximum control authority and noise contribution. Possible solutions have been suggested and are being evaluated.
- Participation in a DCS Peer Review at GSFC and the ST7-DRS Preliminary Design Review at JPL.

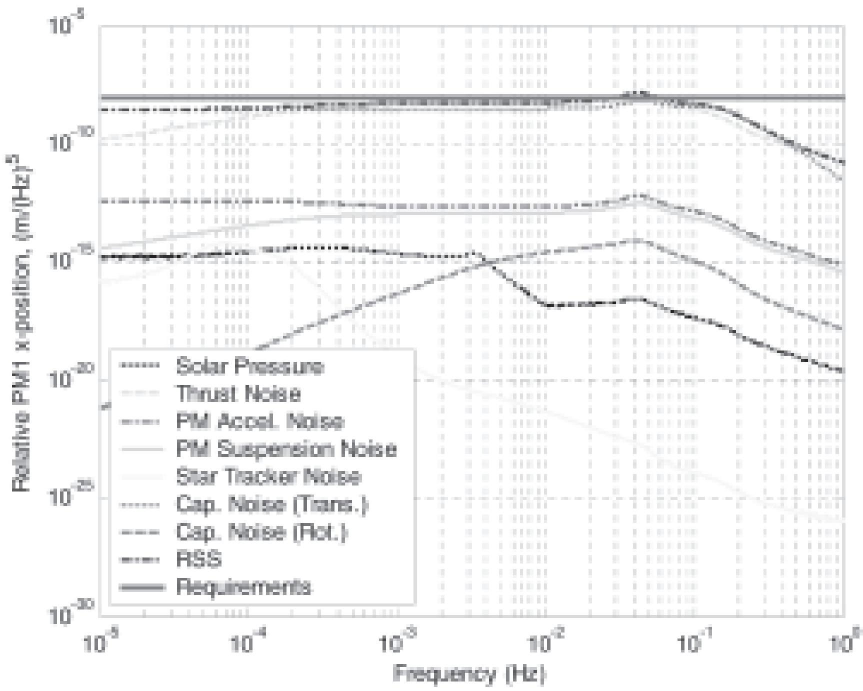

Figure 2-9. Root PSD for ST-7's Reference Test Mass Relative Position in X

[Technical contact: Oscar Hsu]

2.1.13 Time History of Events and Macroscale Interactions during Substorms (THEMIS)

http://sprg.ssl.berkeley.edu/THEMIS/

The GSFC MESA Division has signed a Letter of Commitment to support the University of California at Berkeley's THEMIS mission. THEMIS is a MIDEX Phase B mission. The MESA division is providing consultation in the areas of attitude/orbit control and determination and GNC systems. MESA has provided ground flight dynamics software for use by Berkeley. The software includes the Goddard Trajectory Determination System (GTDS), Goddard Maneuver Analysis (GMAN) and the Multi-Mission Single-Axis Stabilized Spacecraft (MSASS) Attitude Determination System. The Goddard Technology Commercialization Office (TCO) is in the process of licensing this software to Berkeley for use for the THEMIS mission. The MESA Division will also provide technology, consisting of onboard algorithms, to fly on THEMIS. The technology is called CelNav and is an onboard orbit determination system using celestial measurements to determine the spacecraft orbit autonomously. The MESA Division will support experiments using CelNav during the mission.

[Technical contacts: Mark Beckman, Robert DeFazio]

2.2 Operational Missions

2.2.1 Earth Observing System (EOS) Aqua

http://eos-aqua.gsfc.nasa.gov/

The Aqua spacecraft was launched May 4, 2002 on a Delta II 7920-10L expendable launch vehicle from the Western Test Range at Vandenberg Air Force Base in California with a planned mission lifetime of six years. Aqua is the lead spacecraft in the PM train of the EOS AM & PM constellations. The Goddard Space Flight Center (GSFC) Aqua Flight Dynamics Team (FDT) has provided post-launch checkout support, Flight Operations Team (FOT) training, and continuing Flight Dynamics (FD) analytical support for attitude and orbit anomaly resolution during the past fiscal year.

Two types of attitude determination systems (ADS) are available in the Aqua Flight Dynamics System (FDS), a coarse, real-time ADS (RTADS) and an offline, more accurate ADS. The offline ADS provides fine attitude determination, onboard computer (OBC) attitude determination validation, and attitude sensor calibration utilities. One of the primary FD ADS requirements is to provide an independent confirmation of the OBC attitude determination performance (Aqua requirement is ±25 arcseconds per axis, three-sigma). All Aqua instrument teams use the downlinked OBC attitude quaternion for science data processing, so the onboard attitude solution accuracy is extremely important.

Validation of the onboard attitude estimates by the FDT was made very difficult due to several spacecraft anomalies. Soon after the Moderate Resolution Imaging Spectro-radiometer (MODIS) instrument calibration was completed, the MODIS team identified a large yaw attitude oscillation (greater than 100 arcseconds) correlated with orbital period by comparing the MODIS observational data with known geolocation references. Several possibilities were explored including ground data processing errors, thermally induced science instrument or attitude sensor alignment shifts, or other science instrument anomalies. After several weeks of analysis by a combined investigation team, the MODIS yaw anomaly was finally traced to an inconsistency between the OBC star catalog and the OBC ephemeris. FD analysts ultimately proved this theory.

The OBC ephemeris is uplinked daily in Mean of J2000 (M-J2000) coordinates and the onboard star catalog is stored in Mean of J2000 coordinates. But the star positions were incorrectly changed to Mean of Date (MoD) coordinates by applying a precession correction in the OBC flight software (FSW) prior to their use in the onboard attitude determination process. The precession correction is used to compensate for the periodic motion (~25,000 years) of the Earth's rotation axis relative to the ecliptic plane, but was unnecessary since the two original coordinate systems were compatible.

The difference between M-J2000 coordinates and MoD coordinates (precessed star positions) varies approximately 50 arcseconds/year and had grown to approximate ±150 arcseconds for the current time difference between the two coordinate systems (~3 years between 2000 and 2003). The coordinate system inconsistency caused the yaw oscillations because the OBC target attitude quaternion was derived from the OBC ephemeris (M-J2000), but the attitude was computed from MoD star positions. The coordinate system discrepancy resulted in an ecliptic latitude dependency (explaining the orbital period correlation) and manifested primarily as yaw motion, although roll and pitch were also affected. The FDT had not noted the discrepancy in previous OBC attitude validation compares because only the OBC and FD ADS attitude quaternions were compared (which are coordinate system independent) vs. Euler angles. The solution was to generate a software patch eliminating the star position precession correction in the onboard FSW. This was implemented shortly after testing and the FSW team, MODIS team, and FDT analysts completed simulations. The results of the precession patch are shown in Figure 2-10, Aqua Euler Angles, below; the roll and pitch values continued to approach zero as time progressed with some minor residual offset (see text below).

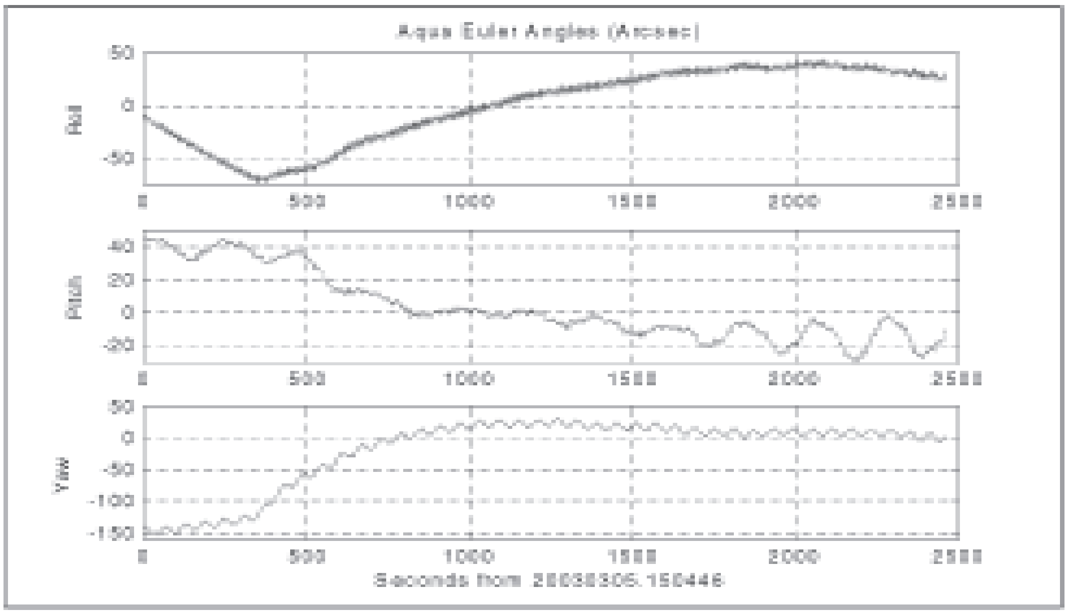

Figure 2-10. Aqua Euler Angles with Control SystemFix

An algorithm was proposed, developed, and tested by the FDT to correct the previous MODIS attitude telemetry by reversing the precession correction in the downlinked attitude quaternions. This approach was implemented in the Aqua ground system and previously collected MODIS science data were reprocessed. After correcting for the large coordinate system error, a smaller effect became observable. OBC validation results revealed systematic offsets in the pitch and roll attitudes of 13 and 11 arcseconds, respectively. The FDT found that a 125 milliseconds (one minor cycle) timetag error in star tracker 1 (ST-1) would exactly account for the observed offsets. The hypothetical error source was investigated and confirmed by the spacecraft manufacturer FSW team as a star tracker timetag error in the onboard processing. The Aqua FSW team will implement a patch to correct the ST-1 timetag error (~11/2003), but an undesirable side effect would be a small attitude offset as compared to pre-ST-1 patch data. The FDT suggested an approach to eliminate the attitude offset by re-calibrating both star tracker alignments to maintain a consistent attitude reference and will provide the corrected ST alignment matrices for simultaneous activation with the timetag patch.

After corrections were applied for these factors, the OBC attitudes differed from ground calculations by less than 1 arcsecond in their mean values, but oscillations in the differences resulted in standard deviations of 8.1, 5.5, and 8.0 arcseconds for roll, pitch and yaw, respectively. These represent the best current estimates of onboard attitude accuracy. The exact source of these oscillations is still under investigation but several correlations have been made. Although the relative alignment of the two star trackers was correlated with the star tracker baseplate temperature and the OBC gyro bias estimates varied regularly with the same period as the temperature variation, no simple correlation between these biases and temperature has been found. It should be noted that the current attitude accuracy estimates are well within Aqua mission requirements.

The FOT identified recurring problems with meeting the predicted OBC ephemeris accuracy requirement (less than 300 meters after 24 hours onboard) and notified the FDT. The FDT and Flight Dynamics Facility (FDF) analysts responsible for the definitive ephemeris generation investigated the history and analyzed potential sources of the problem. It was determined that the FOT was using a mission-averaged coefficient of drag (C_d) value. Although useful for long-term product generation, it did not provide the best C_d estimate for short-term predictive products, such as the OBC ephemeris, due to the dynamic nature of F10.7 solar flux effects on C_d estimates. The institutional, FDF real-time orbit determination system (RTODS) is used by FDF analysts to generate the daily definitive ephemeris used by the FOT for OBC ephemeris production, FOT product generation, and for some science data processing. The filter-based RTODS system provided an estimated C_d value with each daily ephemeris delivery, but this only reflected the computed C_d value for the last observation. Variation of the computed C_d between sequential RTODS solutions could significantly vary, so a parametric study was proposed and completed by FDT & FDF analysts using several durations (1, 3, & 6 complete orbits) of averaged C_d values for a previous 29-day solar cycle. The C_d values were then used to generate predicted ephemerides and the results were compared to the definitive ephemeris for each day. The statistics showed that all the average C_d's examined performed better than the mission average or the instantaneous RTODS C_d values for short-term product generation. A recommendation was made to the FOT regarding the C_d and appropriate changes were implemented in the Aqua ground system to accommodate the input source. The FDS was enhanced to provide a user option to use different C_d values for short- and long-term products. A significant improvement in meeting the OBC ephemeris requirement was observed after the enhancement.

The FDT also discovered that the OBC ephemeris accuracy requirement as written in the FD section of the Aqua Ground System Requirements Document did not include the allocation for latency (time between last collected definitive ephemeris data and OBC ephemeris activation - currently approximately12 hours). An additional 100 meters were allocated for this error source, but not included in the original FD allocation. The discrepancy in the OBC ephemeris accuracy requirement was researched by the FDT with the Aqua Project and spacecraft manufacturer. All agreed the latency allocation should have been included and the new FD OBC ephemeris accuracy requirement is now less than 400 meters after 24 hours onboard.

The FDT has also provided support for the planning, simulations, and demonstration of the Aqua inclination adjust (delta-I) attitude maneuver capability. The first Aqua delta-I maneuver was planned for 10/7/2003 with a 10-minute burn duration due to spacecraft and physical constraints on maneuver location. A series of similar delta-I maneuvers preformed near an equinox will be required to insure the required orbit parameters are maintained.

The Aura spacecraft (the last member of the PM train) will benefit from the resolutions to the Aqua anomalies. It is the same spacecraft bus with a planned launch date no earlier than (NET) March 2004.

[Technical Points of Contact: Lauri Newman, David Tracewell]

2.2.2 EOS Terra

http://terra.nasa.gov/

The FDAB supported the analysis, planning, and execution for a set of Deep Space Calibration (DSC) attitude maneuvers for the Terra spacecraft. The purpose of the maneuvers was to provide the Terra instruments with a view of deep space and a known irradiance source (the Moon) in order to allow refined instrument calibration.

FDAB personnel participated in several discussions with the instrument teams, Mission Director, and Flight Operations Team (FOT) to pin down all the details of the maneuvers, and performed analysis to predict optimal times for the maneuvers. Each maneuver consisted of a 360° pitch slew, carefully timed to optimize instrument data collection. We considered parameters such as lunar position relative to the Terra orbit plane, optimum lunar radiance in the lunar cycle (which is roughly 2 days prior to full Moon), spacecraft day/night constraints, and TDRSS availability, to determine optimum slew times.

The first DSC slew was performed on March 26, 2003. This maneuver was timed such that the Moon would not enter the instrument fields of view. FDAB personnel provided pre-maneuver planning support, on-console support for real-time attitude determination, and post-maneuver analysis support. The maneuver went exactly as planned and no anomalies occurred.

The second DSC slew was performed on April 14, 2003. This maneuver was timed such that the Moon would pass nearly dead-center through the instrument fields of view. Again, FDAB personnel provided pre-maneuver and on-console support. This maneuver also went exactly as planned, with no anomalies.

[Technical contact: Mark Woodard)]

2.2.3 Far Ultraviolet Spectroscopic Explorer (FUSE)

http://fuse.pha.jhu.edu/

FUSE gives astronomers the unique capability of observing the universe's far ultraviolet portion of the electromagnetic spectrum (approximately 90 to 120 nanometers). Studying this light, astronomers are able to better understand the conditions just after the big bang, as well as the chemical evolution of galaxies and interstellar gas clouds.

In the fall of 2001, the FUSE spacecraft lost two reaction wheels. There is also a high probability that all of the gyros may be lost. With the mission in jeopardy, the Johns Hopkins University and Orbital Sciences Corporation (OSC) requested the FDAB to review the recovery procedures, attitude and rate determination methods, and control system designs. Working closely with OSC, the FDAB studied two attitude and rate determination methods to determine the best fit for the mission. The FDAB also developed a simple safe-hold design that will maintain a power positive attitude in the event that attitude determination and all of the gyros are lost.

The attitude and rate estimation system developed by the FDAB combines two algorithms into a hybrid algorithm, Hybrid Integrated Rate Parameters (HIRP). Both rely on the measured Earth magnetic field and an onboard model of the expected magnetic field. The system uses the magnetic field measurement along with previous measurements and a kinematic model to describe the spacecraft motion (see Figure 2-11). During maneuvers, the kinematic model is replaced by a model of the spacecraft dynamics. The system was compared to a method developed by OSC for validation purposes. Johns Hopkins uplinked the OSC algorithm to FUSE and performed onboard verification tests. During the summer of 2003, another gyro failed. Even though three axes of gyro information are available from two gyro packages, the spacecraft rate is now determined by two gyros and by the estimation algorithm for the axis of the recently failed gyro. Procedures were already in place, which resulted in a smooth transition to derived rate about that axis.

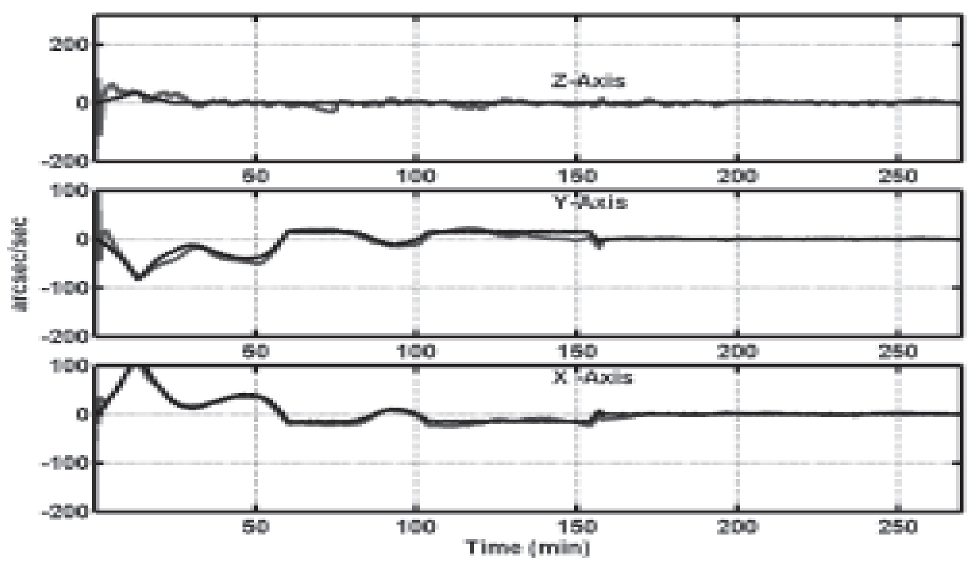

Figure 2-11. FUSE Flight Gyro and Hybrid Integrated Rate Parameters (HIRP) Algorithm Rates

The new safe-hold algorithm is required to point the solar arrays at the Sun during the daylight portion of the orbit and hold the instrument out of the orbit plane without the use of gyros. The algorithm relies on a physical concept: If you apply “B-dot control” to a body that has an internal momentum, that momentum will tend to precess away from the orbit plane. “B-dot control” is simply the difference between consecutively measured magnetic fields. Holding a wheel, parallel to the instrument at near constant speed (internal momentum), the wheel and instrument will precess away from the orbit plane. The wheel is then slightly modulated to maintain Sun pointing. This algorithm was extensively ground tested and uploaded onboard the spacecraft along with other OSC generated software patches. An on-orbit test was successfully conducted during the spring of 2003.

[Technical contacts: David Mangus, Richard Harman, Julie Thienel]

2.2.4 Hubble Space Telescope (HST)

http://hubble.nasa.gov/

The Hubble Space Telescope (HST) project is investigating a Two-Gyro Science Mode for the observatory. With only four of the original six gyroscopes of the Rate Sensing Units (RSU) still working, there is a risk of requiring such a controller sometime before the RSUs are replaced. All three RSUs (six gyros) will be replaced during Servicing Mission 4 (SM-4), planned for May 2005; however SM-4 is currently on indefinite hold due to the Shuttle Program stand-down.

Two-gyro control systems have been successfully implemented on other spacecraft (e.g. International Ultraviolet Explorer in 1985) but are particularly challenging for HST with its demanding pointing requirements. A sequence of 3 controllers is planned, involving Magnetometers (MSS), Fixed-head Star Trackers (FHST), and Fine Guidance Sensors (FGS) each coupled with the remaining two gyros to provide full 3-axis control. A development schedule ending March 2005 is being pursued in which MSS-FHST-FGS controllers are designed, the HSTSIM reference simulation is upgraded and verified, and flight software written and tested. The Two-Gyro Science mode is expected to provide pointing jitter of 30 milliarcseconds, compared to the current level of 7 milliarcseconds. FDAB personnel are working closely with Lockheed Martin and HST Project personnel to develop and verify the ground and flight algorithms.

[Technical contact: Michael Femiano]

2.2.5 Rossi X-ray Timing Explorer (RXTE)

http://agile.gsfc.nasa.gov/docs/xte/xte_1st.html

Since 1995, RXTE has been observing bursts of X-rays that come from high-energy phenomena including black holes, neutron stars, and X-ray pulsars (see Figure 2-12). RXTE performs slew maneuvers to point at various ground selected targets. RXTE can dwell on a target with arcsecond pointing accuracy using high precision gyros and star trackers.

In FY 2003, the Flight Operations Team (FOT) updated the original Generic Trending and Analysis System (GTAS) ground processing system to the new Trending and Plotting System (TAPS) program. During this transition, there were many questions raised about the type and number of tests that should be completed. Working with the RXTE FOT and Chesapeake Aerospace, the FDAB identified a test set that satisfied the questions raised. Initial results showed good correlation between the GTAS and the TAPS for the raw telemetry. Pseudo-telemetry issues are being worked at the time of this report.

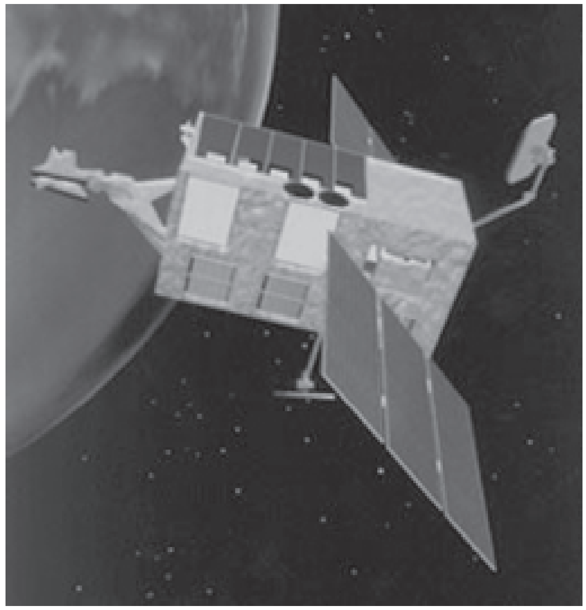

Figure 2-12. Rossi X-ray Timing Explorer (RXTE)

During normal operations, the solar arrays are canted away from the Sun to prevent thermal degradation of the solar panels. If the spacecraft enters safehold mode, the solar arrays are automatically commanded to a position that directly faces the Sun. Within a few orbits, the FOT ground commands the solar arrays to rotate back to a safe condition. Due to cost cuts, the FOT will be required to operate in a “lights out” condition. All FOT operations will occur during normal business hours, Monday through Friday. An initial study showed that entering into safehold for an entire weekend incurs a greater risk of solar panel degradation. The FDAB was actively involved in developing concepts to reduce this risk. The solution was to automatically pitch up the entire spacecraft upon entering into safehold. Before launch, the logic had been simulated and incorporated into the spacecraft by members of the now FDAB and Chesapeake Aerospace. A ground test using FOT procedures and the dynamic simulator successfully verified that automatically pitching the spacecraft as it enters safehold is possible.

[Technical contact: David Mangus]

2.2.6 Tropical Rainfall Measurement Mission (TRMM)

http://trmm.gsfc.nasa.gov/

Spacecraft

The Tropical Rainfall Measurement Mission (TRMM) was launched into a 350 km orbit on November 27, 1997, and boosted to a 402.5 km altitude in August 2001 to conserve fuel. During the past fiscal year, TRMM performed 33 delta-V maneuvers to maintain a frozen, 405 km altitude orbit. In addition, there were 14 yaw maneuvers, designed to keep the Sun on one side of the spacecraft. The -*Y* solar array gimbal started failing, so after much analysis, simulation, and testing, the -*Y* array has been limited to +/- 1 degree rotation, essentially feathering the array during the daylight portion of the orbit.

As part of the continuing effort to improve the accuracy of the TRMM Kalman filter, the magnetic field model parameters were burned to EEPROM so that the model would not have to be updated in the event of a cold processor restart. In addition, on March 4, 2003, the Digital Sun Sensor (DSS) residual tolerance was lowered from 0.2 degrees to 0.1 degrees. This tighter tolerance eliminated data from the edge of the field of view of the DSS, reducing transients in the attitude and gyro bias estimation. On May 19, 2003, the DSS tolerance was reduced further to 0.05 degrees, and the Three-Axis Magnetometer (TAM) B calibration tables were loaded to the spacecraft. If TRMM ever has to use the backup magnetometer, its measurements would now be as accurate as the primary magnetometer measurements.

In July, we updated the onboard values for spacecraft frontal area and mass to increase the accuracy of the onboard ephemeris model. Two strings of solar cells have apparently shorted, but there is no danger to the spacecraft or to the power system.

Ground Attitude Estimation

This past year saw the continuation of the re-engineering of TRMM's mission operations. One subtask of this re-engineering effort was to develop a new system for ground based estimates of the attitude of the spacecraft. This effort analyzed upgrading the current attitude estimation system, but that was deemed too cumbersome for any further development. It was decided to tailor the Multi-mission Three Axis Stabilized Spacecraft (MTASS) attitude estimation system to the TRMM mission. MTASS is a Goddard-developed system for offline and real-time attitude estimation and validation, developed in Matlab. Using documentation of the TRMM telemetry packets, a front-end was developed to ingest the raw telemetry into MTASS where the canned routines to adjust the data and determine an attitude solution reside. MTASS had to be tailored with the parameters of the TRMM sensors to properly adjust the raw data to useable engineering units and measurement vectors. The system was tested and is currently in use operationally. In addition to the basic function of estimating an attitude for the TRMM spacecraft, the processing that would normally be performed by a person has now been automated. This automation consists of not only ingesting the data and processing it, but also checking the data at each point before processing can continue. This has saved countless hours of human operation.

TRMM Controlled Re-entry Planning

Based on orbital debris analysis, TRMM's debris casualty area is 11.3 m^2, and debris casualty risk is 1:4530 if TRMM reenters Earth atmosphere in 2009 by natural decay. This number exceeds the one in ten thousand guideline specified in NASA Safety Standard 1740.14. The numbers quoted here are from the 2002 ORSAT analysis with over 90% of mass analyzed. The results have been consistent with previous analysis. Therefore, controlled reentry for TRMM is necessary.

To support the TRMM project reentry planning effort in 2003, the TRMM GN&C reentry team performed end-of-mission planning that was presented in a review by the Office of System Safety and Mission Assurance (Goddard Code 300). The fist reentry planning was to re-estimate the propellant budget, which is the trigger point for de-orbiting TRMM in the nominal situation. Other important planning includes: design of nominal and contingency trajectories; footprint analysis; examination of the on-orbit hardware status; design and analysis of the reentry control and operation sequence; design, analysis and test of the modified Delta H (momentum management) mode for attitude control at low perigee; and identification of necessary software and table value changes for reentry. Reentry fault detection and correction, both on-board and on the ground, were developed. Important contingency plans were ascertained. In addition, the GN&C reentry team worked together with the operational team and other subsystems to develop an operations timeline and operation procedures, and to re-examine the telemetry rate so that it could fit into the 4 kilobits per second (Kbps) bandwidth.

TRMM Re-engineering

The purpose of the TRMM re-engineering effort is to move most of the Flight Dynamics (FD) functions into the TRMM Mission Operations Center (MOC) using commercial off-the-shelf (COTS) and government off-the-shelf (GOTS) software as much as possible. In the process of re-engineering TRMM we will also automate the functions, and streamline operations in order to reduce the overall cost of satellite operations and Consolidated Space Operations Contract (CSOC) costs and reliance. For the automation of the FD functions we are using the system called TRMM Autonomous Flight Dynamics System (AutoFDS) as shown in Figure 2-13. The products will be scheduled in the AutoFDS system and automatically generated using tools such as FreeFlyer™ and Matlab™. Possible products include station contacts, TDRS contacts, node crossing, shadow times, maneuver planning etc. The TRMM re-engineered system is expected to be operational during the first quarter of FY04.

Figure 2-13. Tropical Rainfall Measurement Mission (TRMM) Re-Engineering: Autonomous Flight Dynamics System (AutoFDS)

COTS applications are being used in the re-engineering of the new TRMM Flight Dynamics System (FDS) since COTS are currently used by most of the Earth Observing System (EOS) missions. In particular, for the TRMM re-engineering effort we are using

FreeFlyer for planning and maneuver products generation and Matlab for attitude products generation. The Quality Assurance (QA) Tool will be used for the quality assurance of all flight dynamics products. The transition of the TRMM legacy systems used at the Flight Dynamics Facility (FDF) to the new TRMM AutoFDS in the TRMM MOC is being done in three phases to minimize risk to mission operations support. The first phase consists of moving the scheduling/planning functions into the MOC. Phases 2 and 3 consist of moving the maneuver and attitude functions, respectively.

The TRMM re-engineering team, consisting of contractor and government personnel, made significant progress in the development, integration, and acceptance of the new TRMM AutoFDS during FY03. Before the team began developing code and scripts to generate the TRMM Flight Dynamics products, a full set of TRMM Flight Dynamics product requirements was required. This was successfully accomplished through several meetings with members of the TRMM FD team, Flight Operations team (FOT), the Mission Director (MD), developers of the AutoFDS, and TRMM re-engineering lead. Once the full set of TRMM FD requirements was identified and documented, the development team was able to proceed with the new system. Soon after that, two PCs were purchased and properly configured as primary and backup in the MOC. An acceptance test, integration test, and operations test plan were developed for each of the three phases. A transition plan, development plan, and failover procedures were developed as well.

The first release of TRMM AutoFDS (Version 1.0) that addressed phase 1 and 2 requirements, was delivered and installed onto the TRMM FD machines in April 2003. The system went through several weeks of acceptance and integration testing. Several releases were necessary to resolve product format problems and accuracy issues found during the acceptance and integration testing of the new TRMM AutoFDS system. The latest release of TRMM AutoFDS, Version 1.0.8, was delivered and installed in the MOC on August 11, 2003. This latest release has successfully gone through acceptance testing and integration testing allowing Version 1.0.8 to move into the parallel operations phase starting August 18, 2003. During the first segment of parallel operations, the FDF has remained prime while the TRMM AutoFDS has been the backup. During this segment the FOT generated table loads from both systems and compared them for accuracy. During the second segment, the TRMM AutoFDS will become the prime system and will generate products that the FOT will use to generate table loads and load them to the spacecraft. The FDF will become the backup system at this point.

Significant progress has also been made in the area of attitude support for phase 3. A Real-Time Attitude Determination System (RTADS) front-end socket connection was developed and installed on the MOC computers in July 2003. This front-end socket connection will allow the spacecraft telemetry data to be properly placed in the appropriate arrays and later be ingested by RTADS. Testing of the RTADS Telemetry Processor (TP) and RTADS is underway. A version of MTASS was also delivered and installed onto the MOC PCs in May 2003. Acceptance testing of the TRMM attitude system is currently being performed.

[Technical contacts: Stephen Andrews, David Mangus, Osvaldo Cuevas]

2.2.7 Wilkinson Microwave Anisotropy Probe (WMAP)

http://map.gsfc.nasa.gov/

The Wilkinson Microwave Anisotropy Probe (WMAP) performed its fourth stationkeeping maneuver (SK4) around the L2 libration point on November 5, 2002. The commanded burn time was 94.31 seconds. After the maneuver, the solar model coefficients were updated to remove the error that had accumulated since launch on June 30, 2001.

The week before stationkeeping 5 (SK5), rain and melting snow caused a water leak in the FLATSAT lab in the basement of Building 1. Water was dripping from the concrete overhead at about 1 gal/day. A system of plastic tenting and drain tiles kept water away from the equipment. SK5 was performed on March 12, 2003, with a commanded burn time of 45.3431 sec. This burn was so accurate that the next stationkeeping maneuver wouldn't be needed for eight months. SK6 is currently scheduled for November 12, 2003.

WMAP went into safehold on Monday, August 11, 2003. The Flight Operations Team (FOT) came up on its daily pass and had trouble communicating with the satellite, which led them to go through RF contingency procedures to establish communication on Transponder Remote Services Node (XRSN) A (current nominal is XRSN B). When communication was established, the spacecraft was found to be in safehold on Attitude Control Electronics (ACE) B (the nominal ACE), pointed safely at the Sun. Further examination showed the Mongoose V main processor had reset, removing the "I'M OK" signal and tripping Safehold. This is very reminiscent of the November 2001 safehold event that was found to be caused by a Single Event Upset (SEU) -susceptible power-on reset circuit in the Mongoose.

By examining the reset clock, it appeared the reset occurred at approximately 9:20 am local time Monday morning. After some troubleshooting to establish that XRSN B was properly functioning, and that the communication problems were likely due to some misconfiguration (either by the ground or coupled with the Mongoose reset), regular communications were established, the software table updates were reloaded, and by approximately 7:30 pm local time, WMAP was back in Observing Mode. The ACE and other Attitude Control System (ACS) hardware and software performed flawlessly during Safehold, holding the spacecraft within one degree of the Sun.

Over the lifetime of the mission (October 1, 2001-00:00:00 through the first week in September, 2003), ~700 days, we've captured 99.81% of the engineering data, and 99.66% of the science data. Most of the losses have been due to the two safehold events.

[Technical contact: Stephen Andrews]

3.0 Study Mission Support

3.1 Autonomous Nano Technology Swarm (ANTS) Advanced Concept

The ANTS NASA advanced concept proposed by the Goddard Space Flight Center's Laboratory for Extraterrestrial Physics envisions the use of a large swarm of small, autonomous spacecraft to explore the asteroid belt. In conjunction with the University of Cincinnati, NASA Langley personnel and NASA Langley contractors, the FDAB has performed trajectory analysis for the transfer trajectory and asteroid proximity operations phases.

[Technical contacts: Greg Marr, David Folta]

3.2 Climate Change Research Initiative Aerosol Polarimetry Sensor (CAPS)

The Climate Change Research Initiative Aerosol Polarimetry Sensor (CAPS) is a satellite study concept in the pre-formulation phase. Its primary objective is to obtain measurements of the distribution of aerosol optical thickness and its spectral absorption. Other objectives include Earth radiation budget measurements, cloud, water vapor and carbon monoxide (CO) measurements. If approved, the target launch date for the mission would be 2007.

The FDAB has provided analysis support for the CAPS study team in the orbit selection process. The primary focus of the analysis to this point has been to determine Sun glint visibility for the candidate orbits and its variation with season and mean local time of the nodal crossings. FDAB also supported an Integrated Mission Design Center (IMDC) study in April 2003 to develop a satellite concept in preparation for proposal development.

[Technical contact: Frank Vaughn]

3.3 Constellation-X

http://constellation.gsfc.nasa.gov/

Constellation-X (Con-X) consists of four spacecraft that will orbit the Sun-Earth L2 libration point. The Con-X spacecraft will be launched two at a time, one year apart, and have a five-year lifetime.

The satellites will be inserted into the Lissajous orbit about L2 via a lunar swingby. The lunar swingby is necessary in order to reduce the amount of onboard fuel carried and the C3 needed from the launch vehicle. C3 is double the combined potential and kinetic energy per unit mass at the Transfer Trajectory Injection (TTI) point of the launch vehicle. Smaller (more negative) values of C3 yield a larger payload capability. In order to increase the number of launch opportunities, a number of phasing loops will be performed prior to the lunar swingby. Figure 3-1 shows a schematic of the transfer trajectory. Different numbers of loops could be considered for various launch days to increase the number of launch opportunities. The FDAB supported the pre-Phase A studies for Con-X.

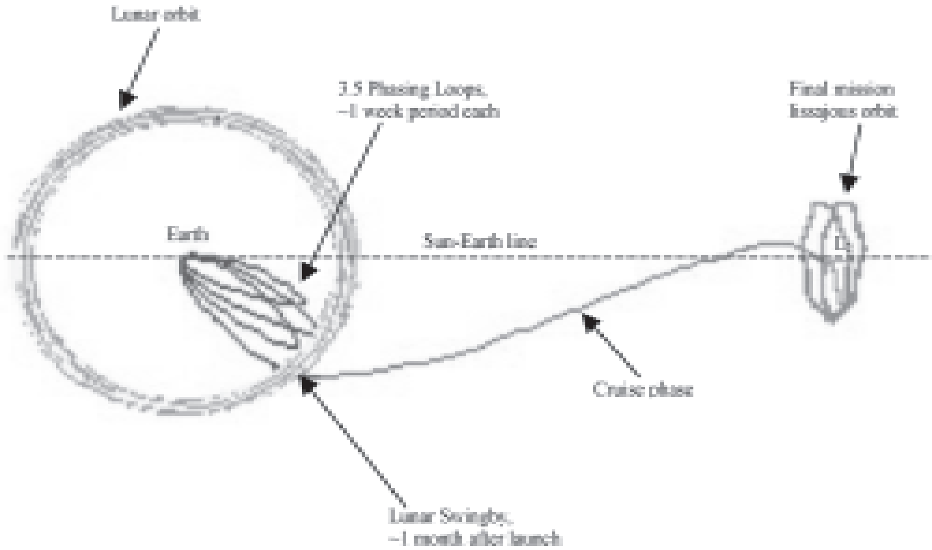

Figure 3-1. Constellation-X Transfer Trajectory

[Technical contact: Mark Beckman]

3.4 Fourier Kelvin Stellar Interferometer (FKSI)

The FDAB is supporting a mission concept for a Sun-Earth L2 libration point mission, the Fourier Kelvin Stellar Interferometer (FKSI), being led by the Goddard Space Flight Center's Laboratory for Astronomy and Solar Physics. The FDAB has analyzed launch vehicle requirements, generated nominal trajectory data, analyzed spacecraft fuel requirements, and performed orbit determination (OD) error analysis.

[Technical contacts: Greg Marr, Steven Cooley]

3.5 Geospace Electrodynamic Connections (GEC)

The Geospace Electrodynamic Connections (GEC) mission is a multi-spacecraft mission managed out of NASA's Solar Terrestrial Probe (STP) Office (Code 460) at the Goddard Space Flight Center. Currently in the formulation phase, GEC plans to use three or four spacecraft to study the Earth's Ionosphere-Thermosphere (IT) system. While this region has been studied before, the coordinated use of multiple spacecraft will allow scientists to discover the spatial and temporal scales on which magnetospheric energy input to the IT region occurs, determine the spatial and temporal scales for the response of the IT system to this input of energy, and to quantify the altitude dependence of the response.

The GEC spacecraft will be launched on a Delta-II 7920 expendable launch vehicle into a 185 km x 2000 km, 83° orbit, no earlier than September 2009. After separation from the launch vehicle, the GEC spacecraft will initialize a "pearls on a string" formation with uneven inter-satellite spacing that will be varied during the course of the mission. The uneven spacing of the spacecraft will allow GEC to be able to resolve a number of different temporal and spatial scales, depending on the final number of spacecraft that are flown. GEC also plans to perform periodic "deep dipping" campaigns where all of the spacecraft will lower their perigee to an altitude near 130 km. There is a goal to have 10, 7-day deep dipping campaigns during the 2-year mission. On-board propulsion will be used to lower perigee to the dipping altitude, to raise perigee back to a safe value at the end of the campaign, and to periodically raise apogee, as it will decay due to numerous perigee passes through the Earth's atmosphere. Propulsion will also be required to establish and maintain the inter-satellite spacings as defined by the GEC science team. The Atmospheric Explorer C (AE-C) mission performed excursions to this altitude in 1975 but the multi-satellite nature of GEC will collect more data while also carrying instruments that AE-C did not carry (e.g. electric field booms).

During FY02, FDAB supported an industry study of GEC conducted through the Rapid Spacecraft Development Office (RSDO). After an open competition of RSDO vendors, two spacecraft contractors were selected (Orbital Sciences Corporation and Spectrum Astro) and received funding for a 100-day study of the GEC concept. FDAB engineers supported the studies by providing mission design expertise in evaluating the two industry designs throughout the study period. Support was also provided at the technical reviews at the mid-term and end-term presentations. At the conclusion of this study, it was determined that a 4-spacecraft, deep dipping mission would not fit under the Explorers Program cost cap set for GEC. At that time, it was decided to conduct a second RSDO study to examine two slightly different GEC mission concepts. The first concept was to fly 3 spacecraft while retaining the desire for 10, 7-day dipping campaigns. The second concept was to fly 4 spacecraft but without the requirement for the dipping campaigns.

During FY03, FDAB personnel worked with the GEC Project Formulation Manager and GEC Systems Engineer to help define orbit requirements for the two mission concepts. The Request for Offer (RFO) was submitted to the RSDO in early 2003 and responses from industry were received in March. Following an evaluation of these responses, three contractors were selected to perform a 5-month study of the two concepts. These contractors included Orbital Sciences Corporation and Spectrum Astro from the first study and Astrium GmBH, based in Germany. As in the first study, FDAB personnel supported kick-off meetings and the mid-term and final reviews of each of the three contractors' designs as well as provided trajectory design consultation to the GEC project. At the completion of the study in late FY03, results of the studies will be reported to both NASA Headquarters and to the GEC Science and Technology Definition Team (STDT) to decide which mission scenario (3 dipping or 4 non-dipping) to choose. Following this decision, the GEC Instrument Announcement of Opportunity (AO) will be released. Spacecraft acquisition will be provided through the Goddard Rapid Spacecraft Development Office (RSDO).

[Technical contact: Michael Mesarch]

3.6 Laser Interferometer Space Antenna (LISA)

http://lisa.gsfc.nasa.gov/

The baseline mission of the Laser Interferometer Space Antenna (LISA) is to detect and observe gravitational waves from astrophysical sources in the frequency band 0.1-100 mHz. There are many potential sources within this band that are easily detectable given the design sensitivity of LISA (strain of 10^{-23} (S/N=5)). Possible sources include galactic binaries, massive black holes in distant galaxies, and primordial gravitational waves. LISA will be comprised of three identical spacecraft separated by 5 million kilometers forming an equilateral triangle. The constellation of three spacecraft will be in heliocentric orbit phased such that the triangle makes a “pin-wheel” motion about its center with a period of one year. Each spacecraft will encompass two freely floating proof masses. Each leg of the triangle will act as a single arm of an interferometer that will be used to measure any change in the distance between the distant proof masses. Each spacecraft will have two incoming and two outgoing laser beams for a total of six laser links. These links will have to be established sequentially at the start of the mission, and the spacecraft control systems must aim their lasers at each other with pointing motions less than 8 nanoradians per root Hertz in the LISA science band.

FDAB personnel supported the LISA mission in a number of areas: dynamics and control modeling and analysis; design and analysis of Disturbance Reduction System (DRS) control; and acquisition control. Each of theses contributions is described in the following paragraphs.

A complete model of the LISA formation consisting of three spacecraft was developed. This model includes the complete rigid-body model of three LISA spacecraft in the science mode (57 degrees of freedom). Each spacecraft model includes designs for the Attitude Control Subsystem (ACS), to maintain the pointing of the two telescopes with respect to two incoming beams from the other spacecraft; the Drag Free Control (DFC), which commands the positioning of the spacecraft to center about the Proof Masses (PM); the proof mass suspension control, to maintain the position and attitude of the proof mass with respect to its caging; and the telescope articulation loop, to maintain the optical link between the spacecraft as the angle between the spacecraft varies according to the natural propagation of the orbits of the spacecraft. Point-ahead compensation is also included to deal with the relative motion of the spacecraft due to their different orbits. Figure 3-2 shows the root power spectral density for the pointing error of one of the telescopes in two axes. The peak level of about 4 nanoradians per root Hertz meets the requirement of 8 nanoradians per root Hertz with over 100 percent margin. The 57-DOF LISA model will also serve the integrated modeling and analysis activities, in particular, the integrated controls-optics analysis of the LISA formation.

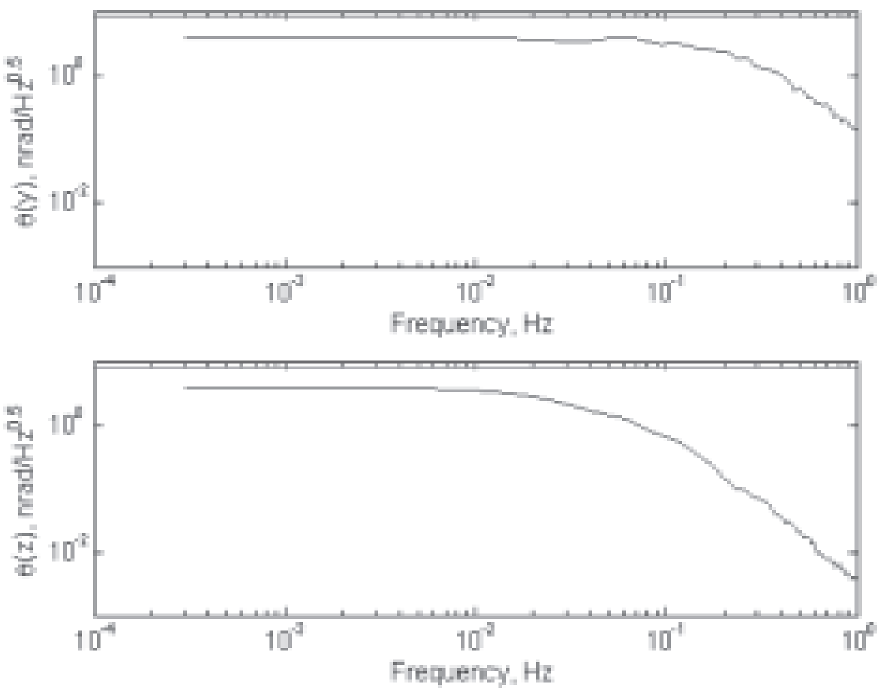

Figure 3-2. Root Power Spectral Density for LISA Telescope Pointing

An acquisition strategy for establishing laser links among the three spacecraft was developed. The proposed strategy defocuses the outgoing laser beam by a factor of 10 to encompass the accuracy and alignment of the star tracker, and hence avoids the need for time-consuming scans. It uses an array of available sensors with varying degree of resolution to lock in one laser link at a time. The procedure uses the star tracker first, followed by the Charge Coupled Device (CCD) sensor and quad cell mode (in intensity mode), and ends with heterodyne differential wavefront tilt measurement from the quad detector. Because of potential stray light issues and the 100 times dimmer incoming beam, the local is turned off until the start of the heterodyne wavefront sensing. Models and simulations have been developed and used to demonstrate the efficacy of the proposed strategy. Figure 3-3 shows a typical pointing error for one telescope throughout the acquisition process with measurements from finer sensors added every 250 seconds.

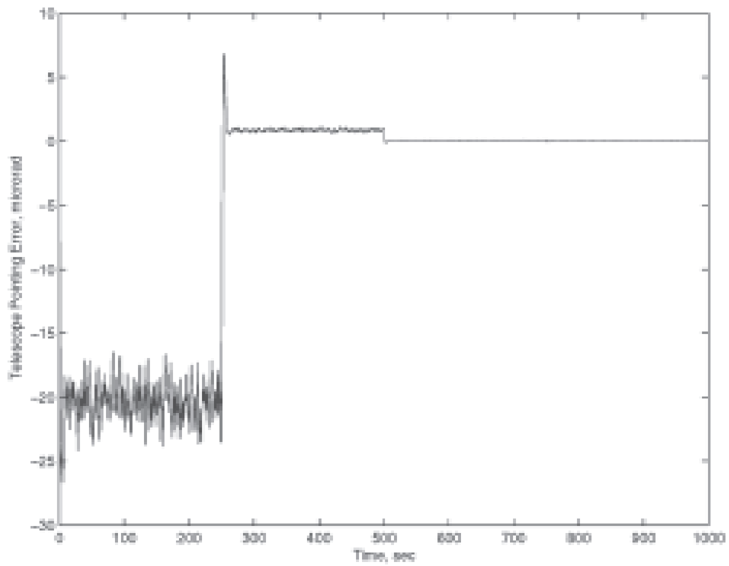

Figure 3-3. LISA Beam Pointing Error Throughout Acquisition

[Technical contact: Peiman Maghami]

3.7 Lunar Science Explorer

The Lunar Science Explorer (LSE) principle investigators visited the Integrated Mission Design Center (IMDC) the week of March 4, 2002 and again the week of April 2, 2002. The LSE is a Discovery Class mission designed to obtain a detailed topography map of the Moon. The mission will map the surface of the Moon over 2 years, using laser altimeters. The mission orbit was chosen to be circular, with a 25 km mean altitude above the lunar surface. The lunar potential model is not similar to the Earth. Mass concentrations (Mascons), dense areas in the lunar structure, greatly affect a predictable orbit. Analysis to compute an orbit that would not vary by more than +/-5km was performed. Figure 3-4 depicts the variation in the altitude as the orbit is maintained using frequent stationkeeping maneuvers. This altitude was chosen to maximize science while minimizing the fuel budget, or delta-V cost, of orbit maintenance (14 m/sec per month). The direct transfer option was chosen after a comparison with Weak Stability Boundary (WSB) and low-thrust options. The direct transfer takes 4.7 days and requires 3 delta-V maneuvers to capture and lower the altitude about the Moon. No significant savings could be identified with the WSB, and the low-thrust option was too power-intensive. The total mission delta-V will be 1460 m/sec.

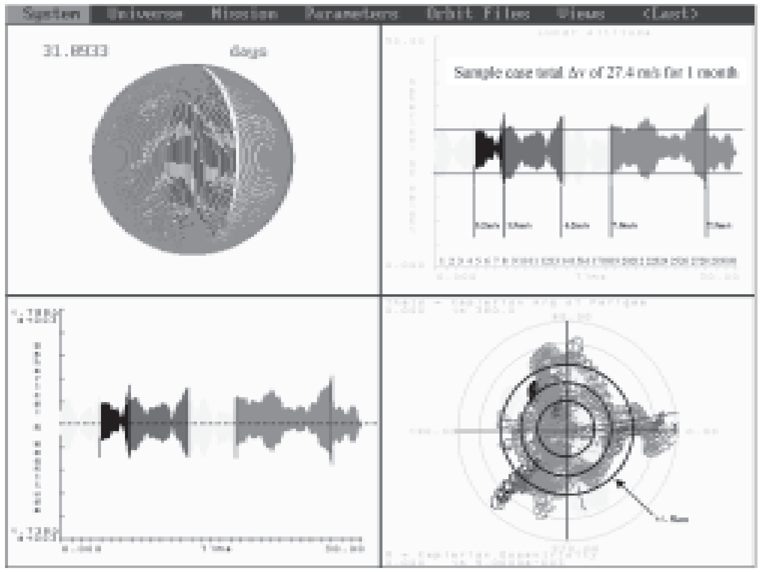

Figure 3-4. LSE Orbit Altitude Variation Over the Lunar Surface

Orbit determination for LSE will be quite challenging. In order to provide the science quality requested, orbit determination accuracy to 1 meter (radial) is necessary. However, at 30 km altitude, the uncertainty in the lunar potential model gives a radial uncertainty of 28 m (as determined by Lunar Prospector orbit determination results). The only way to meet the OD requirements is to use LSE Doppler data to generate an updated lunar gravity model specific to the 30 km polar orbit. Mars Global Surveyor OD accuracy improved three-fold, from beginning of mission to end, due to gravity model tailoring.

[Technical contacts: David Folta, Mark Beckman]

3.8 Office of Biological and Physical Research (OBPR)

The objective of the Office of Biological and Physical Research (OBPR) satellite program concept from Glenn Research Center (GRC) is to provide frequent opportunities for biological and physical science flight experimentation to complement ongoing Shuttle and International Space Station (ISS) activities. Availability of unmanned free-flyers with return-to-Earth capability will increase access to space and minimize time from selection to flight for experiments that do not require human-tended operations.

To date, the FDAB has provided analysis support for a number of IMDC studies to evaluate the feasibility of, and/or develop, viable OBPR mission concepts in concert with ARC, Langley Research Center (LaRC), Marshall Space Flight Center (MSFC), and the Jet Propulsion Laboratory (JPL). Another IMDC concept study will be scheduled in early FY2004.

[Technical contact: Frank Vaughn]

3.9 Revolutionary Aerospace Systems Concepts (RASC)

Under a NASA RASC study, a Sun-Earth L2 libration point orbit, which remains close to the Sun-Earth line is being studied. In conjunction with NASA Langley personnel and NASA Langley contractors, the FDAB has performed transfer trajectory analyses, stationkeeping analyses, and preliminary navigation analyses.

[Technical contacts: David Folta, Greg Marr, Steven Cooley]

3.10 Solar Imaging Radio Array (SIRA)

Mission design and formation flying analysis was completed for the Solar Imaging Radio Array (SIRA) concept. Several orbit regimes and formation designs were investigated to meet both the science and communication requirements and to minimize fuel. Orbit trades to compare to a desired retrograde orbit of less than 160 Earth radii (Re) (10^6 km), for a stable orbit were completed. There are several constraints for this mission. Earth-constellation distances greater than 50 Re (less interference) and less than 100 Re (link margin) are desired. The plan is to have up to 16 microsats in a formation, each with its own "downlink." The density of "baselines" should be uniformly distributed for imaging. Satellites can be randomly distributed on a sphere to produce the density pattern result. The formation diameter of approximately 25 to 50 km is needed to achieve desired angular resolution. The satellites will be "approximately" 3-axis stabilized. Lower energy orbit insertion requirements are always desired. Eclipses should be avoided if possible. Defunct satellites should not "interfere" excessively with operational satellites.

The orbit trades included Sun-Earth L1 libration orbits, drift away orbits, Earth-Moon L4 libration orbits, and Distant Retrograde Orbits (DRO). The Earth-Moon and DRO orbits are shown in Figures 3-5 and 3-6.

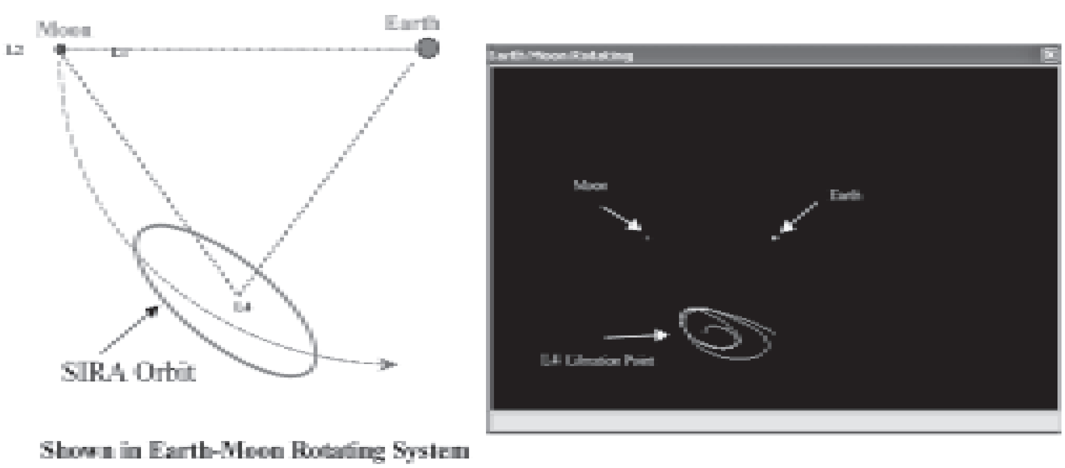

Figure 3-5. Earth Moon L4 Libration Orbit for SIRA

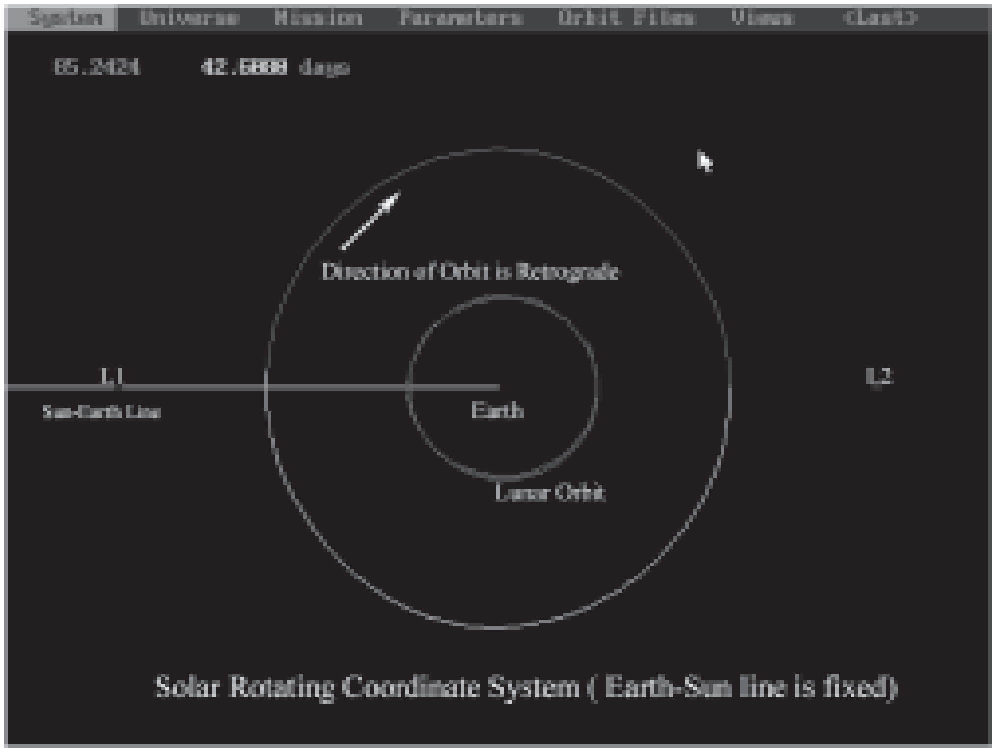

Figure 3-6. Distant Retrograde Orbits for SIRA

The Earth-Moon libration orbits and the DRO orbits are stable and do not require any stationkeeping maintenance during the 2-3 year mission lifetime. Transfers to these orbits were computed and included long duration transfers to minimize the insertion delta-V requirements and lunar gravity assists to enable very short transfer times. The orbit trades included analyses of shadows, antenna coverage, launch vehicle energy requirements, and insertion delta-V costs.

The formation of SIRA is very interesting in that it is comprised of 16 spacecraft uniformly distributed on a sphere with a radius of 25km. Formations are all baselined to maintain a sphere of 25km radius. Constant low thrust control was applied assuming 0.1 micro-Newtons (mN) and a simple proportional-derivative (PD) controller to hold position. A uniformly distributed sphere was computed using Robert Bauer's "Uniform Sampling of SO3" algorithm presented at the 2001 Flight Mechanics Symposium. Spacecraft locations on the sphere were held with respect to each other in either a strict or a loose formation control using the PD controller. The spacecraft as controlled are shown in Figure 3-7. The U-V plane was also assessed and a figure of merit was computed.

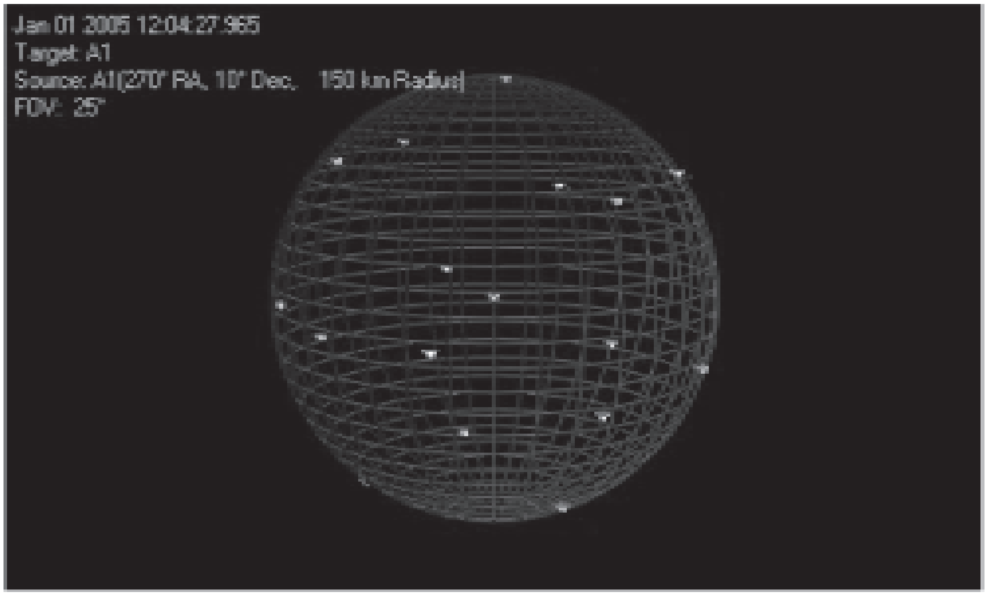

Figure 3-7. Uniform Sphere Placement

[Technical contacts: Did Folta, Frank Vaughn, Bo Nassz]

3.11 Venus Sounder for Planetary Exploration (VESPER)

The Flight Dynamics Analysis Branch is supporting a Venus orbiter Discovery Proposal, Venus Sounder for Planetary Exploration (VESPER), being led by the Goddard Space Flight Center's Laboratory for Extraterrestrial Physics. VESPER will integrate key measurements with atmospheric models to investigate the coupled processes of chemistry and dynamics in the Venus middle atmosphere. The VESPER goal is to conduct a tightly focused study of the Venus atmosphere as part of a larger NASA program of comparative planetology. VESPER consists of a spacecraft and an atmospheric entry probe. The FDAB has analyzed launch vehicle requirements, generated nominal trajectory data, and analyzed potential probe impact locations for 2008 and 2010 launch opportunities.

[Technical contact: Greg Marr]

3.12 Integrated Mission Design Center (IMDC)
http://imdc.gsfc.nasa.gov/

The Integrated Mission Design Center (IMDC) is a human and technology resource dedicated to innovation in the development of advanced space mission design concepts to increase scientific value for NASA and its customers. The IMDC provides specific engineering analysis and services for mission design and provides end-to-end mission design products.

The FDAB provides engineering expertise in the areas of trajectory design and attitude control. The trajectory engineers from the FDAB provide critical mission specific analysis and design for mission trajectories. Attitude control engineers provide expertise in the refinement of ACS requirements, sensor selection, actuator sizing, component placement specification, control mode designs, and risk assessments. Due to the nature of the innovative missions proposed by the customers, innovative solutions are envisioned in order to meet the science requirements. ACS engineers also identify “tall-poles” that require a revision of science requirements. Many of the tall-poles are related to formation sensing, tight attitude requirements and fuel constraints. In addition to the services mentioned above, ACS engineers also provide critical cost analyses and trade studies to determine the lowest cost configuration that will meet the science requirements.

A wide range of mission types were supported, including low earth orbit, geosynchronous (GEO), libation-point, and formation flights (at L1, L2, etc). Some missions required point solutions while others required new technology concepts to achieve the science goals. Many of the formation studies required innovative ways of solving the problems posed by the customers.

[Technical contacts: Paul Mason, James Morrissey, and Charles Petruzzo]

4.0 Technology Development Activities

4.1 Advanced Mission Design

The ultimate goal of the Advanced Mission Design activity is to develop and integrate improved methods that allow us to design more complex missions and to minimize the cost of flying these missions. From a simple request to reduce the amount of fuel to achieve an orbit to computing unique trajectories using new mathematical methods, this task aids us in helping spacecraft engineers and scientists accomplish their goals. From this effort, we incorporate basic components of optimization methods into our mission design software tools. We also add capabilities to directly use a branch of mathematics called dynamical systems. Using these methods, new orbits were established that encouraged science proposals and enabled new missions. Besides designs of single trajectories, this activity also supports a suite of general design tools that allow optimal geometric designs that meet the constraints for Distributed Space Systems, which have multiple spacecraft in formations.

This work crosses many GSFC projects and NASA enterprises as it involves all orbit types, many spacecraft, and provides for new technologies. A portion of this work was a continuation of the Goddard Mission Services Evolution Center (GMSEC) and Earth Science Technology Office (ESTO) funded activities for applications to both Earth and Space Science Enterprises (ESE and SSE). The Technology Readiness Level (TRL) of the research varies, as some optimization techniques are clearly understood, but how we should best apply them to orbit design is not. Recent successful optimization analysis has been performed in support of the Global Precipitation Measurement (GPM) constellation, the Solar Dynamics Observatory (SDO) orbit transfers, the James Webb Space Telescope (JWST) libration orbit, and the Laser Interferometer Space Antenna (LISA) mission. The LISA formation and control optimization consists of three spacecraft flying five million kilometers apart in the shape of an equilateral triangle.

This work contributes to GSFC and NASA by helping to reduce the cost of access to space, providing innovative technologies, building capabilities, and transferring this knowledge to the academic and commercial communities. The technical investigations and developments further support the resident expertise particularly within the context of libration point orbit analysis, transfer trajectory design, and general formation establishment and maintenance. The work enhances the theoretical understanding of the multi-body problem and offers the advantages available by incorporating the dynamical relationships into formation flying design. The models and techniques developed provide immediate results for mission support, thus enhancing GSFC participation in proposals while expanding capabilities. The Advanced Mission Design work described here covers flight dynamics areas important to all trajectory design. These include optimization of orbits to meet science and engineering requirements while minimizing maneuver impacts, application of new mathematical methods to ensure optimal design, investigation of unique orbit design, and the development of new utilities and algorithms to support GSFC missions.

4.1.1 Unique Orbits

We analyzed unique orbits using a dynamical systems approach. Orbits in the vicinity of the collinear libration points in the Sun-Earth and Earth-Moon systems serve as excellent vantage points for scientific investigations involving the Sun, planetary, and Earth/Moon environments. We will continue to focus significant development and operations activities for NASA in support of such missions. GSFC missions involving libration-point orbits include the Constellation-X formation of X-ray telescopes, the Micro-Arcsecond X-ray Imaging Mission (MAXIM) formation, the Stellar Imager formation, and JWST. The use of multiple spacecraft in a distributed approach to perform interferometry and optical measurements not achievable by a single spacecraft was one of the major drivers in this effort. Trajectory design and pre-launch analysis, as well as on-orbit operations and performance evaluations, for these missions is increasingly challenging as more complex missions are envisioned throughout the upcoming decades.

[Technical contact: David Folta]

4.1.2 Invariant Manifold Research

With the increasing interest in missions involving Sun-Earth and Earth-Moon libration points, it is necessary to further develop numerical, and possibly analytical, tools to assist in trajectory design in multi-body regimes, including libration point orbits. Thus far, Earth to libration point orbit transfers as well as libration point orbit to Earth arcs have been computed using a number of different numerical procedures including exploitation of the invariant manifolds associated with a particular periodic libration point orbit (or quasi-periodic Lissajous trajectory). More recently, transfers between different three-body systems are a new focus for potential mission scenarios. Continuous computation of individual manifolds using numerical integration is not efficient or even practical for some applications.

For the problem of system-to-system transfers, the goal is the intersection of two manifold tubes – one from each system. A maneuver at an intersection point will shift the vehicle from one tube to the other. If the manifolds are generated and stored in some form, determination of the intersection curve can be accomplished. Figure 4-1 shows an example of a large Sun/Earth L1 stable manifold and various Earth/Moon L2 unstable manifolds at different phases of the Moon.

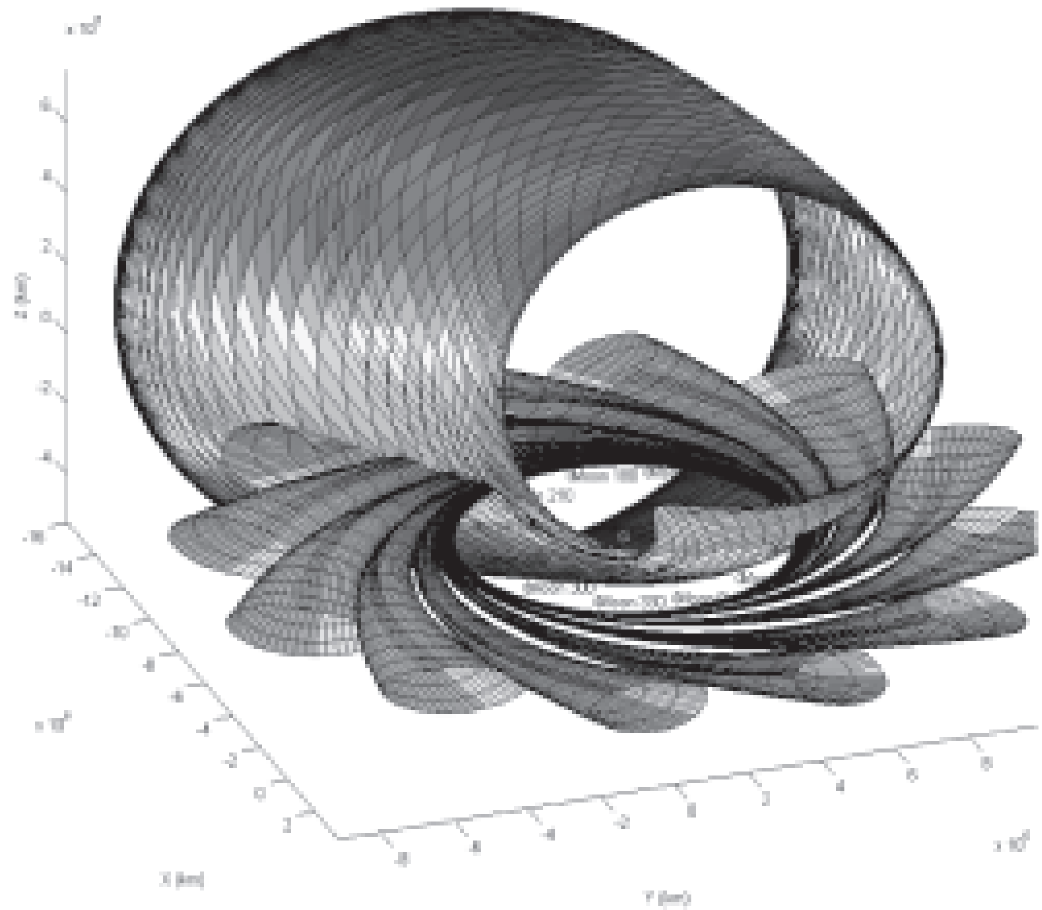

Figure 4-1. Multiple Sun/Earth and Earth/Moon Manifolds

In a joint research effort with Purdue University, the Flight Dynamics Analysis Branch (FDAB) is investigating different approaches to storing manifold data. Splines and low order functional approximations both provide accurate representations. Figure 4-2 shows a mapping from a family of libration-point orbits into defined cells in space that surround the volume. The cells are sufficiently small such that the manifold data within the cells is nearly flat and can be represented with low order functional approximations. Cell sizes and shapes are tailored to the local shape of the manifold volume. Position and velocity functions for the manifold data within the cells can be found with standard fitting algorithms.

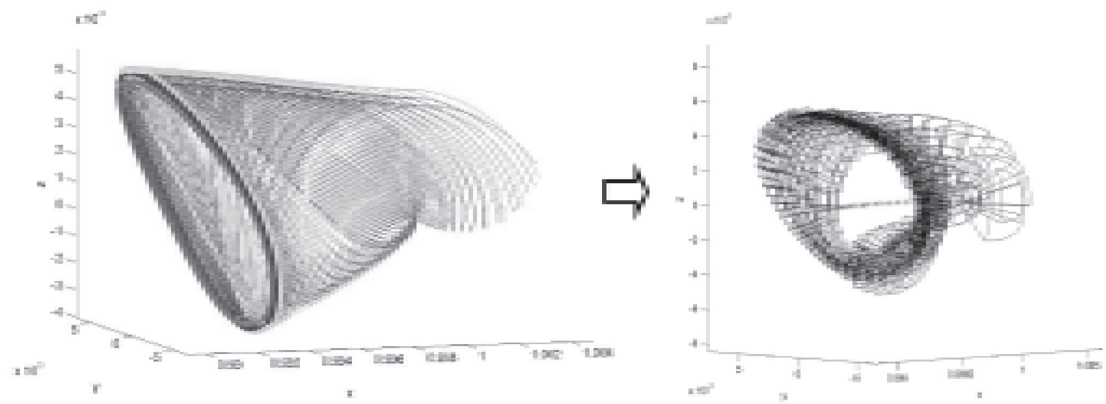

Figure 4-2. Libration Orbit Family Mapping into Cells

[Technical contacts: Mark Beckman, David Folta]

4.2 Advanced Navigation Technologies

Autonomous navigation research was the primary focus of this technology area. This work provides highly accurate onboard inertial and relative navigation options for multiple satellites. This enables many advanced mission concepts such as formation flying, solar sailing, and low-thrust orbit transfer. It also enhances autonomy for all aspects of mission operations including maneuver planning and execution, communication signal acquisition, real-time onboard attitude determination and control. The FDAB approach maximizes design flexibility by providing a single navigation software system, GEONS, for multiple mission scenarios. The approach optimizes use of available sensor data onboard the vehicles. It reduces mission life-cycle cost for single and multi-spacecraft platforms, by minimizing ground and tracking operations, and by reducing the development and test cost of autonomous navigation while increasing the efficiency of the navigation process.

4.2.1 Navigation Accuracy Guidelines For Orbital Formation Flying

Some simple guidelines based on the accuracy in determining a satellite formation's semi-major axis differences have been found to be useful in making preliminary assessments of the navigation accuracy needed to support such missions. These guidelines are valid for any elliptical orbit, regardless of eccentricity. Although maneuvers required for formation establishment, reconfiguration, and station-keeping require accurate prediction of the state estimate to the maneuver time, and hence are directly affected by errors in all the orbital elements, experience has shown that determination of orbit plane orientation and orbit shape to acceptable levels is less challenging than the determination of orbital period or semi-major axis. Furthermore, any differences among the member's semi-major axes are undesirable for a satellite formation, since it will lead to differential along-track drift due to period differences. Since inevitable navigation errors prevent these differences from ever being zero, one may use the guidelines to determine how much drift will result from a given relative navigation accuracy, or conversely what navigation accuracy is required to limit drift to a given rate. Since the guidelines do not account for non-two-body perturbations, they may be viewed as useful preliminary design tools, rather than as the basis for mission navigation requirements, which should be based on detailed analysis of the mission configuration, including all relevant sources of uncertainty. These results were presented at the 2003 American Institute of Aeronautics and Astronautics (AIAA) Guidance, Navigation, and Control (GN&C) conference.

[Technical contact: Russell Carpenter]

4.2.2 MMS Orbit Determination Analysis

Global Positioning System (GPS) Enhanced Onboard Navigation System (GEONS) relative navigation simulations for the Magnetospheric Multi-Scale (MMS) Phase 1 1.2x12 Earth radii orbit tetrahedral formation demonstrated that science objectives of 100 km absolute position and 1% of the separation (100 m near apogee) relative position accuracy can be met using any of three options: two-way ground station Doppler and crosslink measurements processed on the ground, GPS for all satellites with or without crosslink, or GPS for local and crosslink from all remote satellites. The latter two options are significantly more accurate and could be implemented onboard, which would potentially lead to operational cost savings. The crosslink measurements significantly reduce relative navigation errors. Figure 4-3 illustrates some of these results, which were presented in greater detail at the 2003 Flight Mechanics Symposium.

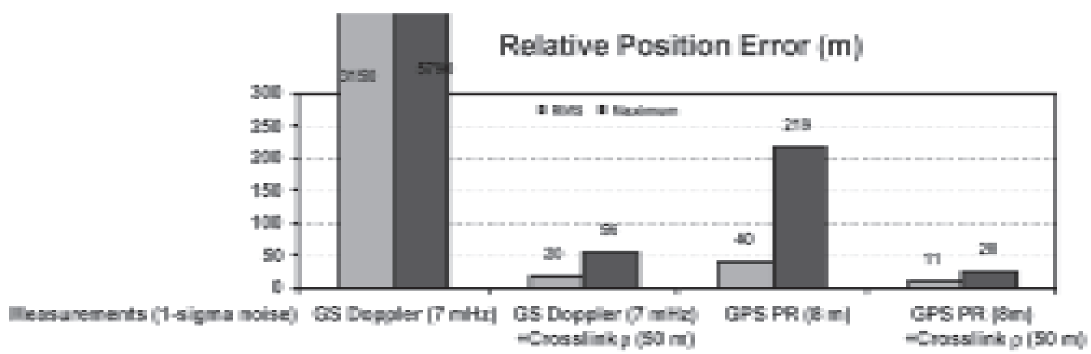

Figure 4-3. MMS Orbit Determination Accuracy Comparison

[Technical contacts: Russell Carpenter, Cheryl Gramling, Michael Moreau]

4.2.3 JWST Navigation Requirements Analysis

GEONS navigation simulations for JWST's L_2 orbit demonstrated that definitive mission support requirements of ≤ 50 km and ≤ 20 mm/s error (three-sigma) can be met using Deep Space Network (DSN) tracking of one 30-minute contact per day (baseline ground navigation scenario), Moon-to-Earth and star-to-Earth celestial object measurements (proposed onboard navigation scenario) assuming solar radiation pressure modeling errors are ≤ 1%, and momentum unload delta-velocity modeling errors are ≤ 1.2 mm/s. Figure 4-4 presents some of these results, which were presented in greater detail at the 2003 Flight Mechanics Symposium.

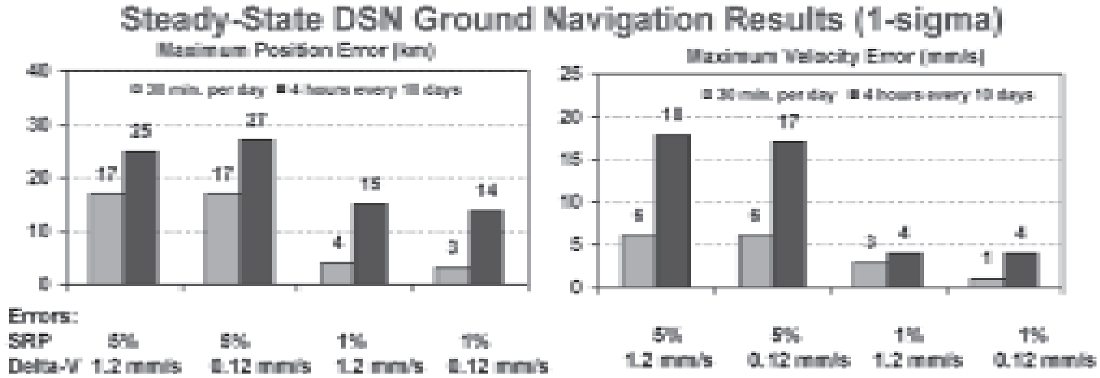

Figure 4-4. JWST Navigation Requirements Analysis Results

[Technical contacts: Mark Beckman, Cheryl Gramling]

4.2.4 GPS Enhanced Orbit Determination (GEODE) Flight Demonstration on STS-107 CANDOS/Low Power Transceiver (LPT) Experiment

GPS navigation was performed on the Communications and Navigation Demonstration on Shuttle (CANDOS) experiment flown on Shuttle mission STS-107. The CANDOS experiment consisted of the Low Power Transceiver (LPT) that hosted the GPS Enhanced Orbit Determination (GEODE) orbit determination software. All CANDOS test data were recovered during the mission using the LPT's Tracking and Data Relay Satellite System (TDRSS) uplink/downlink communications capability. All in-flight navigation objectives were met. Results were compared with the Best Estimate of Trajectory (BET) from NASA Johnson Space Center (JSC), with JSC real-time ground navigation vectors, and post-processed solutions from the Goddard Trajectory Determination System (GTDS). Post-flight analysis of these ephemeris comparisons, estimated covariances, and measurement residuals yielded root mean square GEODE/GEONS accuracy estimates of 25-35 m in position and 2.5-4.5 cm/sec in velocity. Figure 4-5 shows some of these results, which were presented in greater detail at the 2003 Flight Mechanics Symposium.

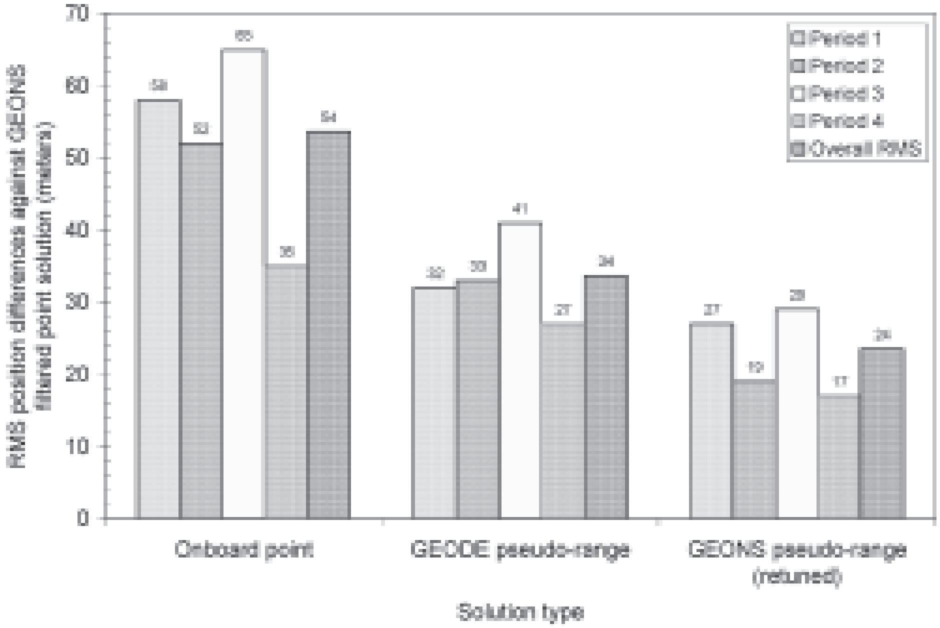

Figure 4-5. GPS Navigation Comparison on CANDOS Experiment

[Technical contact: Russell Carpenter]

4.2.5 GEONS Flight Software Development

Two new versions of GEONS were developed and tested, and an additional version is undergoing final acceptance testing for an expected delivery prior to the end of the year. These versions include the following capabilities:

- Release 1.4 (delivered)
  - Ground station range processing capability to support analysis of ground navigation scenarios
  - Relative state vector estimation for ground station, celestial object and point solution measurements
- Release 2.0 (delivered)
  - Singly-differenced GPS carrier phase measurement processing, which improves relative navigation accuracy to 10 cm level
  - Maneuver targeting algorithms, which extend GEONS to support formation control
  - Antenna offset models for multiple antennas, providing more accurate modeling and support for an attitude determination capability
- Release 2.1 (to be delivered prior to the end of 2003)
  - Horizon and Sun sensor measurement processing for spin-stabilized satellites

[Technical contact: Russell Carpenter]

4.2.6 Orbit Determination of the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) Mission Using Tracking Data Relay Satellite (TDRSS) Differenced One-Way Doppler Tracking Data

Over an approximately 48-hour period from September 26 to September 28, 2002, the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) mission was intensively supported by TDRSS. The TIMED satellite is in a nearly circular low-Earth orbit with a semimajor axis of approximately 7000 km and an inclination of approximately 74 degrees. The objective was to provide TDRSS tracking support for orbit determination (OD) to generate a definitive ephemeris of 24-hour duration or more with a 3-sigma position error no greater than 100 meters, and this tracking campaign was successful. An ephemeris was generated by GSFC personnel using the TDRSS tracking data and was compared with an ephemeris generated by the Johns Hopkins University's Applied Physics Laboratory using TIMED GPS data. Prior to the tracking campaign, FDAB engineers performed OD error analysis to justify scheduling the TDRSS support.

[Technical contact: Greg Marr]

4.3 Distributed Spacecraft Technologies

Spacecraft formations are a subset of the global collection of multiple spacecraft missions, classified as Distributed Space Systems (DSS). In general a DSS is a collection of two or more space vehicles designed to accomplish similar or shared objectives; an end-to-end (information) system consisting of two or more space vehicles, coordinated flight management, and an integrated infrastructure for data acquisition, storage, analysis, and distribution. In contrast, a formation is comprised of multiple spacecraft with the ability to cooperatively detect, maintain, and agree on the appropriate maneuver to maintain a desired position and orientation. Formation flying is enabling technology required to maintain the relative separation, orientation, or position between or among the formation spacecraft.

Overall responsibility for DSS technology development resides with the Guidance, Navigation & Control Systems Engineering Branch of the Mission Engineering & Systems Analysis Division. DSS and formation flying technology development is supported by Principle Investigators within FDAB with specific focus areas shown in Table 4-1.

DSS Formation Flying Technology Area	Principle Investigator
Earth-Orbiting Formation Control	David Quinn
Earth-Orbiting Formation Design	Steven Hughes
Fault-Tolerance, Decentralized Control, Relative Navigation	Russell Carpenter
High-Altitude Relative Navigation	Michael Moreau
Libration-Point Formation Control	Richard Luquette
Libration-Point Formation Design	David Folta

Table 4-1. DSS Formation Flying Technology Area Principal Investigators

The following subsections describe various formation flying technology development initiatives pursued by FDAB during FY2003.

4.3.1 Benchmark Problems for Spacecraft Formation Flying Missions

Due to the wide variety of ideas for DSS missions, researchers working in this area have had difficulty in identifying candidate problems to which they should apply their innovations. Researchers have also had difficulties in making relevant comparisons between algorithms and technologies when they are applied in different circumstances. To address these concerns, some relevant benchmark problem descriptions that cover a range of the types of missions that are of interest to NASA over the next couple of decades have been proposed. These problems are not specific to any current or proposed mission, but instead are intended to capture high-level features that would be generic to many similar missions. These benchmark problems are as described below:

- **Low Earth Orbit**: The low Earth orbit benchmark formation is defined with respect to a reference trajectory, which follows a near-circular, Sun-synchronous orbit with a nominal altitude of 400 km. This benchmark formation features six, three-axis stabilized spacecraft. Three are equally spaced in each of two oppositely inclined "projected circular" formations 500 m in diameter.
- **Highly Elliptical Earth Orbit**: The average position of the highly elliptical orbit benchmark formation follows a 1.2x18 Earth radii orbit, lying approximately five degrees above the ecliptic plane, where the initial line of apsides is parallel to the direction to the Sun, and apogee is opposite the Sun. There are four spin-stabilized spacecraft that must form a 10 km regular tetrahedron at apogee, with arbitrary orientation.
- **Libration-Point Formation**: The libration-point formation follows a medium Lissajous orbit about the L_2 Sun-Earth libration point, with transverse amplitude of approximately 300,000 km and normal amplitude equal to or less than the transverse amplitude. There are 20 three-axis stabilized spacecraft, each a subaperture along an aspherical surface with a 250 m radius. The subapertures are distributed over the asphere in an arbitrary configuration so as to produce a large number of internal baselines for a sparse primary telescope aperture. A single spacecraft is located 100 km away at the focus, along the line of sight to the science target, such that the whole configuration forms a distributed Fizeau interferometer.

[Technical contact: Russell Carpenter]

4.3.2 Autonomous Formation Flying Control of Earth Observing (EO)-1

NASA's first-ever autonomous formation flying mission continued to be an unqualified success. GSFC continued to demonstrate the capability of satellites to continuously fly in formation, to react to each other, and to maintain close proximity without human intervention. This unique advancement highlighted in *Aviation Weekly and Space Technology* allows satellites to autonomously react to each other's orbit changes quickly and efficiently. It permits scientists to obtain unique measurements by combining data from several satellites rather than flying all the instruments on one costly satellite. It also enables the collection of different types of scientific data unavailable from a single satellite, such as stereo views or simultaneously collecting data of the same ground scene at different angles.

On EO-1, formation flying was required to calibrate and compare technological advances made in ground observing instruments that are smaller, less costly, and more powerful. Onboard EO-1, an advanced technological controller called AutoCon provides the capability of autonomously planning, executing, and calibrating satellite orbit maneuvers. On EO-1 it is used for the computation of maneuvers to maintain the separation between the two satellites (EO-1 and Landsat-7). The maneuver algorithm is designed as a universal three-dimensional method for controlling the relative motion of multiple satellites in any orbit. This was then combined with new flight software that is the commercial predecessor of a GSFC sponsored commercial software package called FreeFlyer produced by *a.i.-solutions, inc*., in Lanham, Maryland.

During the year, EO-1 continued to maintain formation with Landsat-7. There have been 77 maneuvers performed since the launch of EO-1 to maintain the formation with Landsat-7. The maneuvers in this fiscal year were computed using the ground-based (but identical to the flight code) version of AutoCon, as the flight code was not turned on due to budget and operations restrictions.

There are many benefits of this onboard formation flying system. Because maneuver calculations and decisions can be performed onboard the satellite, the lengthy period of ground-based planning currently required prior to maneuver execution will eventually be eliminated. The system is also modular so that it can be easily extended to other mission objectives such as simple orbit maintenance for both formation and non-formation flying missions. Furthermore, the flight controller is designed to be compatible with various onboard navigation systems. Onboard formation control enables a large number of satellites to be managed with a minimum of ground support. The result will be a group of satellites with the ability to detect errors and cooperatively agree on the appropriate maneuver to maintain the desired positions and orientations. The formation flying technology flown onboard EO-1 will make distributing scientific instruments over many separate satellites routine and cost effective.

[Technical contact: David Folta]

4.3.3 6 Degree of Freedom (DOF) Nonlinear Control for Formation Flying

Virtual platforms, based on spacecraft formations, form the strategy for improving the spatial and angular resolution achievable for space-based observatories. Stellar Imager and MAXIM are typical missions based on this design concept. Precision formation flying falls among the enabling technologies required for mission feasibility and success. This section describes current research related to control algorithms for precision formation flying. This specific area of research considers the problem of simultaneous control of a spacecraft's orbit and attitude, in order to meet the strict mission requirements (micro-arcsecond pointing and sub-millimeter position control).

Spacecraft orbit and attitude trajectories are governed by nonlinear dynamics, and when combined, allow for six degrees of freedom (6-DOF) in motion. Research targets development of a 6-DOF, nonlinear control algorithm for achieving the design specifications for missions requiring precision formation flying. Algorithm development is based on the assumption that these missions will be stationed near L_2. Hence, the orbital dynamics are characterized by the restricted-three body problem. Further external disturbances are limited to solar pressure and other gravitational sources. Recent work developed and demonstrated a 6-DOF control algorithm. Adaptation is applied to compensate for unknown spacecraft mass properties. Further detail is provided in the paper referenced below. Current work is focused on refining the design and comparing the performance of nonlinear algorithms with linear control designs.

For further information, refer to the following:

Luquette, R. J. and Sanner, R.M., “A Nonlinear, Six-Degree of Freedom, Precision Formation Control Algorithm, Based on Restricted Three Body Dynamics,” 26th AAS Guidance and Control Conference, Feb. 5-9, 2003, Paper No. AAS 03-007.

[Technical contact: Richard Luquette]

4.3.4 Synchronized Position Hold Engage Re-orient Experimental Satellites (SPHERES)

This investigation makes use of Synchronized Position Hold Engage Re-orient Experimental Satellites (SPHERES), which is a spacecraft formation flight test bed breadboard developed by Payload Systems, Inc. (PSI), and the Space Systems Laboratory in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT). SPHERES provides a shirtsleeve environment test bed for the validation of metrology, formation flying, and autonomy algorithms to coordinate the motion of multiple satellites in micro-gravity (e.g. reduced-gravity aircraft flights, Shuttle mid-deck, or the International Space Station). In this investigation, FDAB engineers are adapting candidate distributed spacecraft control technologies developed at GSFC for validation via SPHERES, and defining requirements, interface specifications, and preliminary designs for external payload interfaces, with an end goal of performing formation control experiments onboard the International Space Station (ISS). For its contributions, GSFC will receive approximately one eighth of the on-orbit resources of SPHERES during its time onboard ISS.

[Technical contact: Russell Carpenter]

4.3.5 Tethered Formation Flying

The Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) is a bold new mission concept designed to address fundamental questions about the Universe, including how the first stars formed from primordial material, and the first galaxies from pre-galactic structures, how the galaxies evolve over time, and the cosmic history of energy release, heavy element synthesis, and dust formation is. Ideally, a very large telescope with an effective aperture approaching one kilometer in diameter would be needed to obtain high quality angular resolution at these long wavelengths; however, this approach proves to be too expensive and therefore impractical. Instead, a spin-stabilized, tethered formation is one possible configuration being considered, requiring a more advanced form of formation flying controller, where dynamics are coupled due to the existence of the tethers between nodes in the formation network. To this end, an investigation into the dynamics and control of multiple tethered spacecraft systems was initiated.

The effort is divided into three separate tasks. Task 1 involves working with mission scientists in an effort to understand and document the science requirements of a SPECS class facility. GSFC science and optics specialists are working with engineers from PSI and the Naval Research Laboratory (NRL) to capture the science requirements and flow them down to understand the engineering requirements imposed by the desired science. Using the Generalized Information Network Analysis framework developed at MIT, PSI will then conduct detailed configuration trade studies. Many possibilities will be examined in an effort to conduct a "broadbrush" analysis to get an understanding of the favorable regions in the trade space and suggest candidate configurations capable of meeting the science requirements.

Task 2 involves cooperation between GSFC and NRL in the development of the equations of motion for a rotating multi-tethered system applicable to the study of fundamental dynamic characteristics of a deep space interferometer concept. The system is assumed to be comprised of n-particles inter-connected by any number of tethers in a user defined configuration. The NRL model can be used in either of two modes. In one mode, the user specifies the forces to be applied to the particles and the resulting dynamics are computed. This is the standard means of implementing controls. To aid in the development of control laws for such a complicated system, a second mode was designed into the dynamics model. In the second mode, the user prescribes the desired dynamics and the model determines the forces necessary to produce that motion. It is believed that this capability will aid controls designers in their efforts. NRL's n-particle dynamics model has been implemented into Star Technology's Satellite Dynamics Tool (SDT) application that in turn interfaces with the Analytical Graphics Inc. (AGI) Satellite Tool Kit (STK) application. The result is a system that allows the user to construct n-particles inter-connected by m-tethers in any user-defined configuration. SDT will then use the imbedded NRL model to compute the dynamics of the particles, generating ephemeris data that is handed over to STK for three-dimensional graphical output.

Working with Virginia Tech, Task 3 is examining key linear and non-linear control methodologies that may prove applicable to the problem of tethered formation flying; specifically, gain-scheduled controllers, Lyapunov based non-linear controllers, and robust adaptive controllers. The object is to build upon the dynamics developed in Task 2 in order to create a core dynamics and control model that permits iteration and expansion while maintaining the primary thrust of the tethered formation. The ultimate goal for this task is to develop a set of control laws centered on the core model from Task 2. This will serve as a first-order tool for examining the dynamics and control of a variety of design configurations.

Finally, as the project comes together, the configuration trades will narrow the trade space and identify at least one candidate configuration that will be examined in greater detail. A model of the candidate configuration will be constructed in the SDT application using NRL's dynamics model. Virginia Tech's controls will be imposed on the dynamics, and a comparison will be made to the original requirements for scientific success. In this way, we will have constructed an important capability and taken a crucial step towards making a SPECS-type mission a real possibility.

[Technical contact: David Quinn]

4.3.6 FDAB Support of the Formation Flying Test Bed

The Formation Flying Test Bed (FFTB), located in the penthouse of Building 11, is a research and development facility with a focus on providing a high fidelity, hardware-in-the-loop simulation capability for DSS mission concepts. FDAB engineers have been part of the FFTB team (including GSFC's Code 591 and 580, and Emergent Space Technologies, LLC), working to incorporate existing tools and algorithms into this unique real-time simulation environment. At the center of the FFTB is a flight computer processor including navigation, guidance, and control functionality that would normally reside onboard a spacecraft that is part of a formation. This flight-like computer communicates in real-time with actual hardware devices such as GPS receivers and cross-link communications transceivers, which in turn are being stimulated by actual radio frequency (RF) signals generated by the test bed equipment.

Figure 4-6 is a block diagram of the FFTB setup. The shaded block represents functionality that would normally reside onboard the spacecraft, such as the flight computer, GPS receivers, and RF cross-link devices, while the remaining blocks are part of the simulation environment. The environment block generates spacecraft trajectories and attitude (denoted *x1–x4* in Figure 4-6) by integrating the differential equations of motion and using high-fidelity force models. The environment block accepts control inputs (denoted *u*) commanded by the flight computer, which modify the nominal trajectory as appropriate when thrusts are applied. The GPSSG block represents a GPS RF signal generator that produces GPS signals based on the trajectory data from the environment block; the GPS receivers then track the signals. Communications and data are exchanged between spacecraft using direct serial or TCP/IP connections; however, in the future actual RF cross-link communications will be supported using a Cross-link Channel Simulator (CCS) that will directly connect the cross-link devices and apply signal delays, Doppler shifts, and attenuation based on the simulated relative motion of the spacecraft.

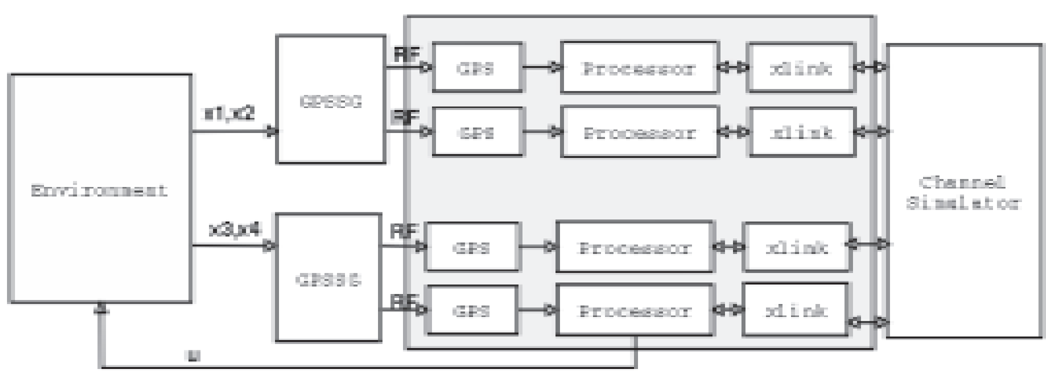

Figure 4-6. Formation Flying Test Bed Block Diagram

One of the significant achievements in the FFTB this year was the integration of the GEONS software as a real-time navigation filter running on the FFTB flight computers. GEONS receives measurements from the GPS receivers (and in the future, from the cross-link ranging device) and produces a navigation solution for each vehicle independently, or solves directly for the relative orbit of the two vehicles. This implementation of GEONS mirrors very closely how the software would run onboard an actual spacecraft computer. The GEONS force models are also being incorporated into the environment computer to generate the reference trajectories for the simulations. Another important achievement was the demonstration of closed-loop formation control of two low Earth orbit spacecraft using GPS receivers and GEONS navigation solutions in the loop.

The FFTB makes it possible to prototype and test relative navigation and formation control algorithms in a realistic environment that closely duplicates critical timing and communications interfaces that must be present onboard an actual spacecraft. Ongoing work includes the integration of the new CCS and simulation of high Earth orbit spacecraft formations such as MMS.

[Technical contacts: Michael Moreau, Bo Naasz]

4.3.7 GPM Autonomous Orbit Maintenance

Maintaining GPM precisely to the reference orbit while allowing frequent non-intrusive maneuver operations is one of the goals of the New Millennium Program (NMP). Maneuver operations frequently result in the loss of science data collection. Combined with a low thrust propulsion system that minimizes attitude perturbations during maneuvers, a proven technology will allow continuous science data collection. For example, without the need to turn instruments off approximately 2 orbits out of every 28 (a two day maneuver frequency) during maneuver maintenance yields a 7% increase in data collection.

An orbit maintenance strategy was chosen that allows maneuver operations to be performed independently from ground intervention. To enable this strategy, the GPM mission will use an autonomous system, called AutoCon. AutoCon is a technology that was successfully flight demonstrated for a year onboard the EO-1 spacecraft to meet autonomous formation flying requirements. The AutoCon system can be easily adapted to GPM altitude maintenance as the basic components of orbit prediction and maneuver planning remain the same as that on EO-1. Furthermore, the formation flying requirements are much more stringent than that of GPM orbit altitude maintenance. The maneuver maintenance algorithm used in the AutoCon system is the Folta-Quinn universal three-dimensional algorithm that will maintain the altitude, eccentricity, and argument of periapsis (if necessary) while allowing operations and environmental constraints to be considered.

Using the maneuver scripts defined during EO-1's formation-flying mission as a starting point, a GPM altitude maintenance maneuver plan was constructed. The simulation was set to plan a maneuver whenever the GPM semi-major axis dropped 0.5km below the reference orbit. The targets and the reference input allow AutoCon to plan a maneuver that will re-establish the orbit at 0.5km above the reference orbit with the correct eccentricity. No changes were made for inclination. An area-to-mass ratio of 0.0033 was used. Figures 4-7 and 4-8 present representative simulation results showing the results of three maneuvers. Each maneuver planned used the same target conditions of raising the mean orbit semi-major axis by 1 km. The eccentricity is controlled through the definition of the reference orbit eccentricity. The orbit decays to the lower boundary where a maneuver was executed. The maneuver is performed as a Hohmann transfer and places GPM into an orbit that is one kilometer higher. After the maneuver, GPM's orbit is propagated until the lower condition is crossed again. As seen, the mean semi-major axis is maintained. Notice that the reference eccentricity trends toward a lower value for this simulation that uses an 8x8 geopotential model and that the GPM eccentricity also follows this trend. The onboard implementation will take into consideration a constant semi-major axis and eccentricity rather than one determined from the propagation of a reference point.

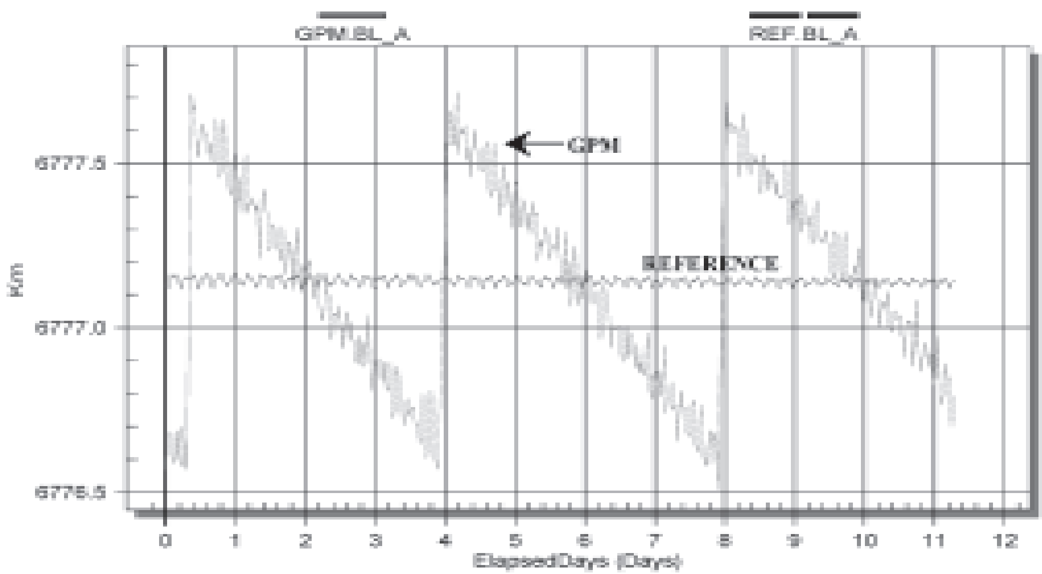

Figure 4-7. GPM vs. Reference Orbit Mean Semi-Major Axis

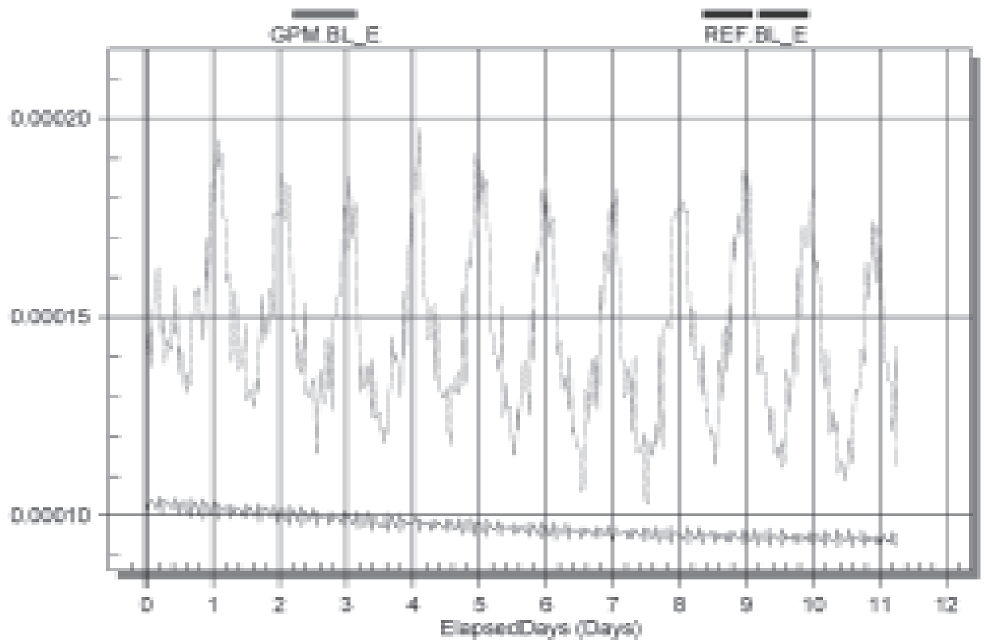

Figure 4-8. GPM vs. Reference Orbit Eccentricity

The use of AutoCon also introduces other benefits into the GPM mission beyond the obvious orbit maintenance and reduced maneuver operations cost. In terms of ground and spacecraft operations, these are:

- Relative to ground operations:
    - Eliminates and reduces ground maneuver operations
    - Eliminates and reduces ground uplinks for maneuvers
    - Eliminates ground post-maneuver calibration assessments
    - Eliminates ground generation of post maneuver products
    - Promotes continuous science data collection
- Relative to spacecraft operations:
    - Provides backup propagation for GPS PIVOT outages
    - Provides data for HGA antenna pointing computations
    - Accepts upload states for propagation and maneuvers
    - Provides fuzzy logic to plan around science or orbital constraints
    - Supports yaw maneuver planning
    - Minimizes ACS propagation code
    - Supports collision avoidance with other resources (e.g. ISS)

The ground operations benefits can result in a real cost savings while improving the quality of science data collected and increasing the amount of science data collected.

[Technical contact: David Folta]

4.4 Attitude Determination Technologies

Under this technology area, new techniques are developed to determine spacecraft attitudes, calibrate attitude sensors, and characterize attitude sensor performance. Prototype algorithms and software packages are developed and evaluated using in-flight as well as simulated data. When successful, these new techniques are migrated to operational ground and flight systems where possible. The two operational ground systems are the Multimission Three-Axis Stabilized Spacecraft (MTASS) system and the Multimission Spin Axis Stabilized Spacecraft (MSASS) system. Both systems have supported more than 18 operational missions. In addition to research into advanced attitude determination and calibration techniques, branch members provide consultation to flight projects on general issues and analysis of methods for attitude determination and calibration as well as sensor modeling and performance. .

4.4.1 Advanced Attitude Algorithms

A new pattern match star identification algorithm was developed which uses a pre-generated pairs catalog to compare pairs of observed stars. The new algorithm works in two steps. The first step involves a lost-in-space pattern match for a given input set of stars. If processing time is not critical, the pattern match can be performed on each set of observed stars. Otherwise, the optional second step is invoked. A second step involves generating an attitude history file, based on the one attitude generated by the pattern match, and gyro data to propagate it. The gyro data is compensated for a bias by looking at the resulting star clumps. This enables potentially large accurate history files. Once the attitude history is generated, a simple direct match can then be used to identify the remaining stars in the batch of data.

An automated gyro calibration algorithm was developed based on a sequential version of Davenport's algorithm. This algorithm estimates gyro scale factor, misalignment, and bias. A best estimate attitude is provided before and after a maneuver along with the *a priori* gyro calibration parameters and gyro data. The gyro calibration algorithm produces updated calibration parameters. Possible uses for this algorithm consist of ground calibration automation as well as onboard gyro calibration. As can be seen in Figure 4-9, the Rossi X-Ray Timing Explorer (RXTE) gyro scale factor, misalignment, and bias calibration parameters are very well defined by the 5th maneuver.

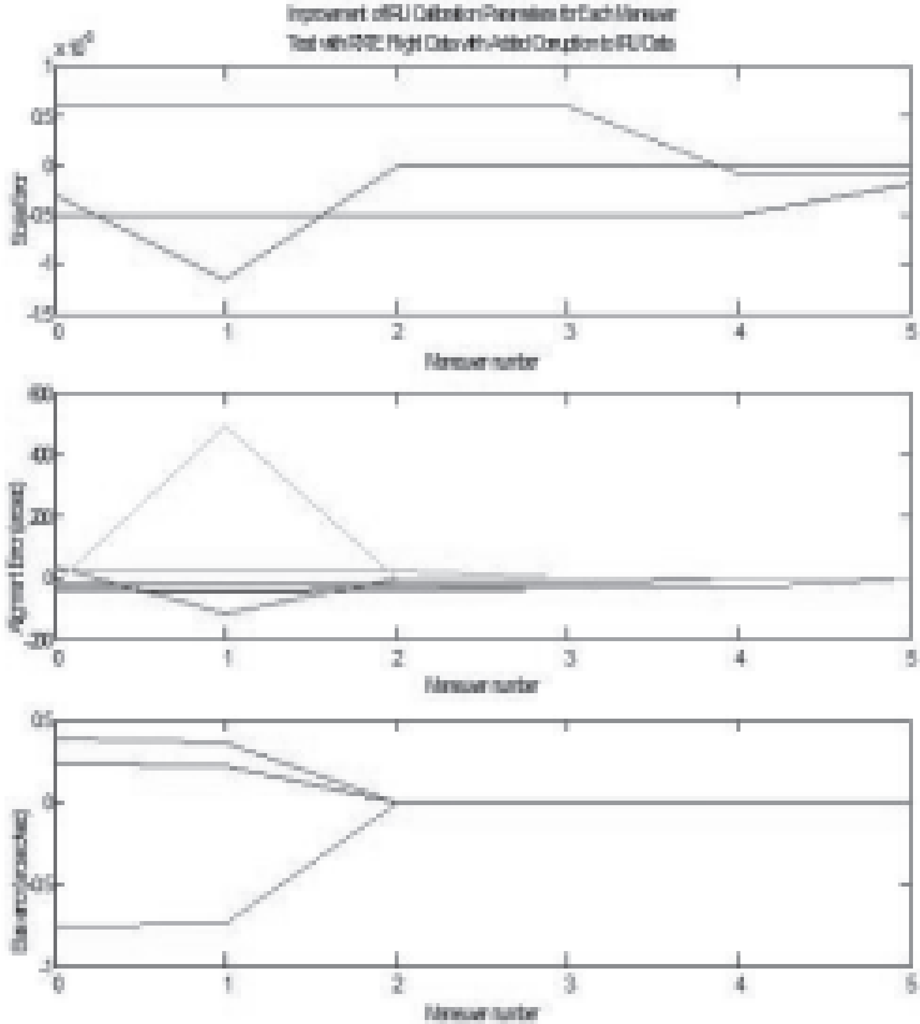

Figure 4-9. RXTE Calibration Parameter Error Versus Maneuver

A new model for converting static Earth sensor telemetry to observation vectors was recently prototyped, tested, and made operational. The model allows for two to four Earth sensor clusters, horizon height, and Earth oblateness. The algorithm was tested using a variety of simulations and the resulting model errors were consistently smaller than the static Earth sensor measurement errors. In the case of four Earth sensor clusters, the resulting model errors were the input white noise.

The Adcole Fine Sun Sensor (FSS) has a standard nine-coefficient transfer function that generates the final angular output. Previous work had improved the accuracy of the transform by adding three extra coefficients to the transfer function. FDAB is tasked with calibrating the FSS's transfer function and current software has been cumbersome to use. Recent work has enhanced the current algorithm, characterized the remaining errors, and provided detailed procedures for successful calibration. Figures 4-10 and 4-11 show the pre- and post-angle errors using the Upper Atmosphere Research Satellite (UARS) flight data for both the alpha and beta angles. The initial FSS calibration errors were a mean of 41 arc-seconds and a standard deviation of 47 arc-seconds. After calibration with the new algorithm and procedures, the resulting errors were reduced to a 1 arc-second mean and a 19 arc-second standard deviation.

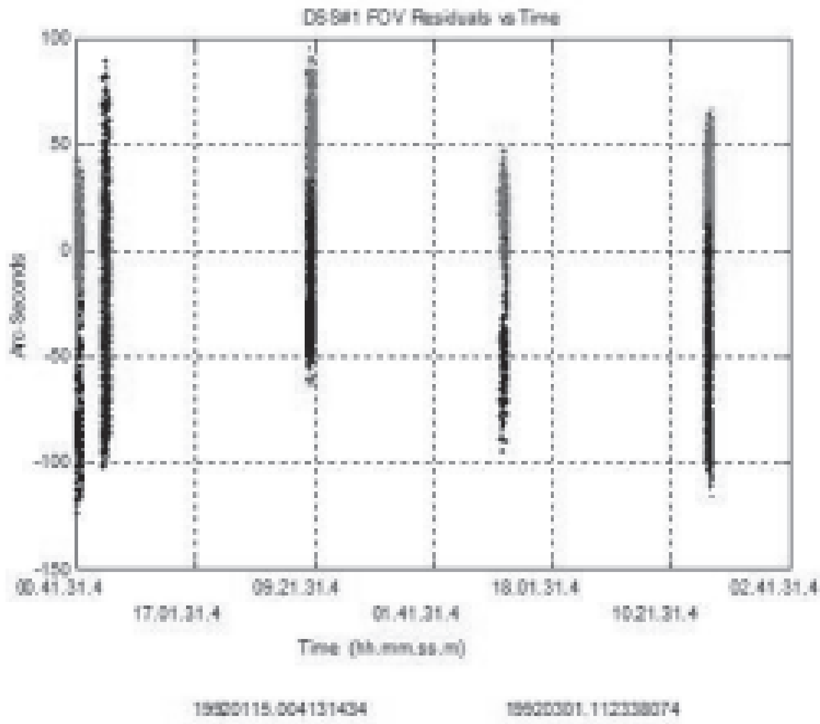

Figure 4-10. Pre-Calibration UARS FSS Alpha and Beta Angle Errors

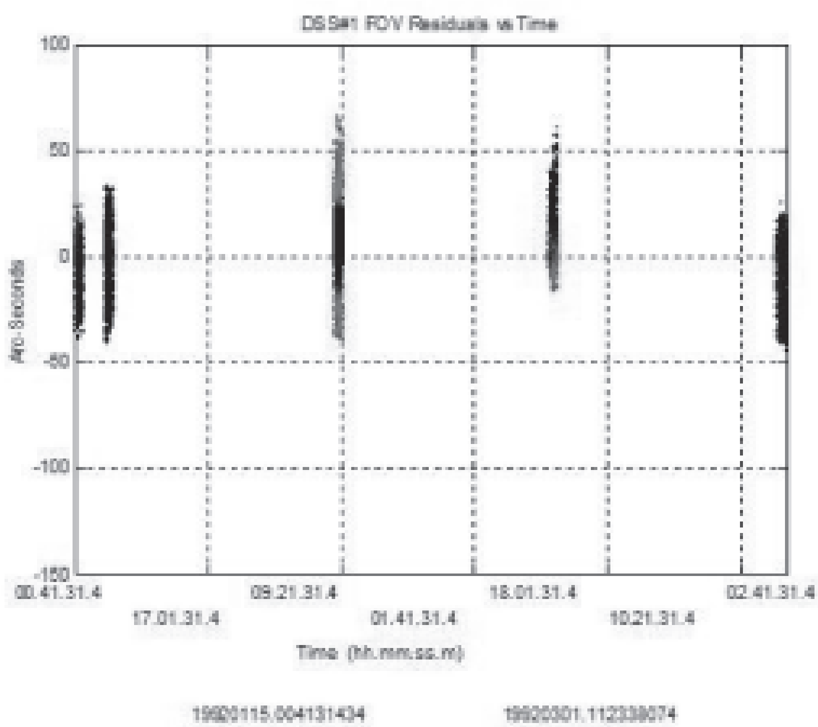

Figure 4-11. Post-Calibration UARS FSS Alpha and Beta Angle Errors

[Technical contact: Richard Harman]

4.4.2 Compound Eye GPS Attitude and Navigation Sensor (CEGANS)

A novel GPS sensor is under development that would provide data for both navigation and attitude, known as the Compound Eye GPS Attitude and Navigation Sensor (CEGANS). The sensor would be equipped with multiple directional antennas mounted on a convex hemispherical surface. Each antenna would be aimed to receive GPS signals from a restricted, but known, visualization cone. By noting which GPS satellites are visible in the field of view of each antenna in the hemispherical array, the attitude of the sensor (and therefore the body to which it is attached) can be estimated to within 3 degrees without resorting to the use of carrier-phase measurements. It is believed that optimization and signal-to-noise techniques can be applied to refine raw attitude estimates from this compact sensor to the sub-degree range.

A simulation study is underway which is beginning to prove that the CEGANS concept can work. To date, the sensor has been given perfect measurement data and so yields perfect solutions. As this idealized simulation is degraded to more closely replicate the true environment (addition of noise models, etc.), a more realistic performance expectation can be formulated. The Star Technologies Satellite Dynamics Tool is proving invaluable in providing the vehicle in which the entire GPS constellation can be modeled as well as the RF interfaces to the satellite employing the CEGANS sensor. US Patent Number 6,594,582 was issued for this work on July 15, 2003.

[Technical contact: David Quinn]

4.5 Micro-Newton Thrust Stand

As part the technology validation effort for LISA and other missions, a thrust stand facility is being developed at Goddard for characterization of the dynamics and noise characteristics of micro-Newton thrusters. The stand is capable of measuring thrust force and noise levels to the micro-Newton and sub-micro-Newton levels, respectively, as required by upcoming mission such as LISA. Figure 4-12 shows the micro-Newton stand inside its vacuum shell. The stand is based on a torsion-balance concept, and is designed to meet the following specifications:

- absolute thrust measurement of 1-100 μN with a resolution better than 0.1 μN
- thrust noise measurement in the 0.1-1000 mHz bandwidth with 0.1 $\mu N/\sqrt{Hz}$ sensitivity
- dynamic thruster response from 0.1 mHz to 10 Hz.

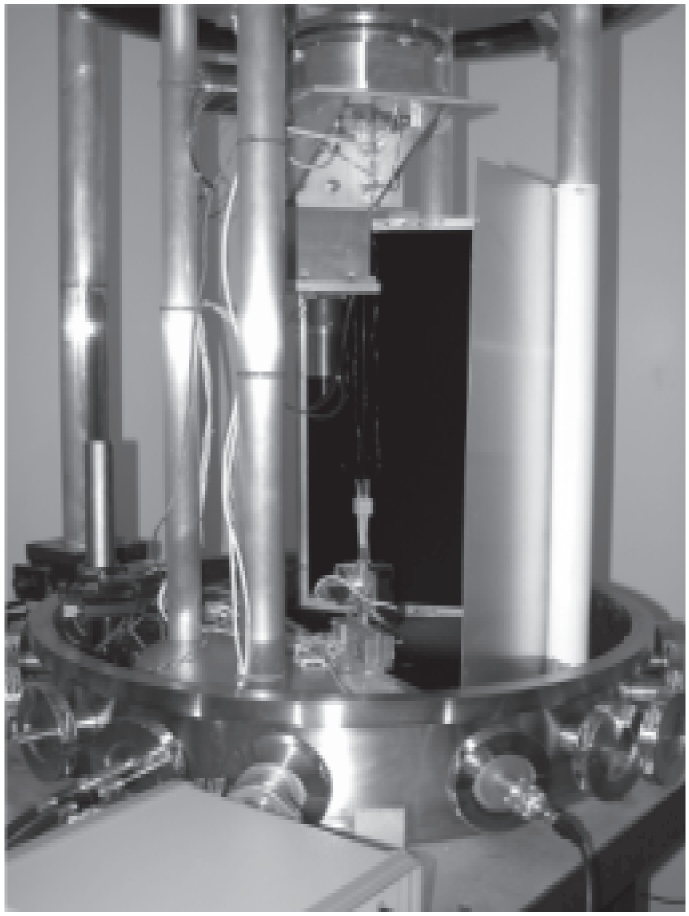

Figure 4-12. MESA's Micro-Newton Thrust Stand

FDAB personnel developed algorithms for the control of the thrust stand. In an open-loop mode, the twist angle measurement is used to compute the thruster force output. However, this mode may not be ideal as it interacts with the dynamics of the stand. Instead, in a so-called "null" mode, capacitive sensing and actuation is used to regulate the twist angle, and the net actuation force/torque is used as a measure of the thruster force output. A digital controller was designed for actuating the capacitors in the null mode. A detailed simulation and analysis model for the thrust stand was developed to analyze the controller performance. The controller takes into account the nonlinear relationship between the electrostatic force, the applied voltage and the gap size, and hence is nonlinear. The controller and the real-time routines were initially tested on a detailed simulation model of the stand and were eventually implemented on the thrust stand. A typical null-mode performance is illustrated in Figure 4-13. Excessive sway of the pendulum mass in the micro-Newton thrust stand operations were observed due to lack of sufficient inherent damping in a vacuum. Hence, the digital control designs were modified to include sway control in order to ease the problem.

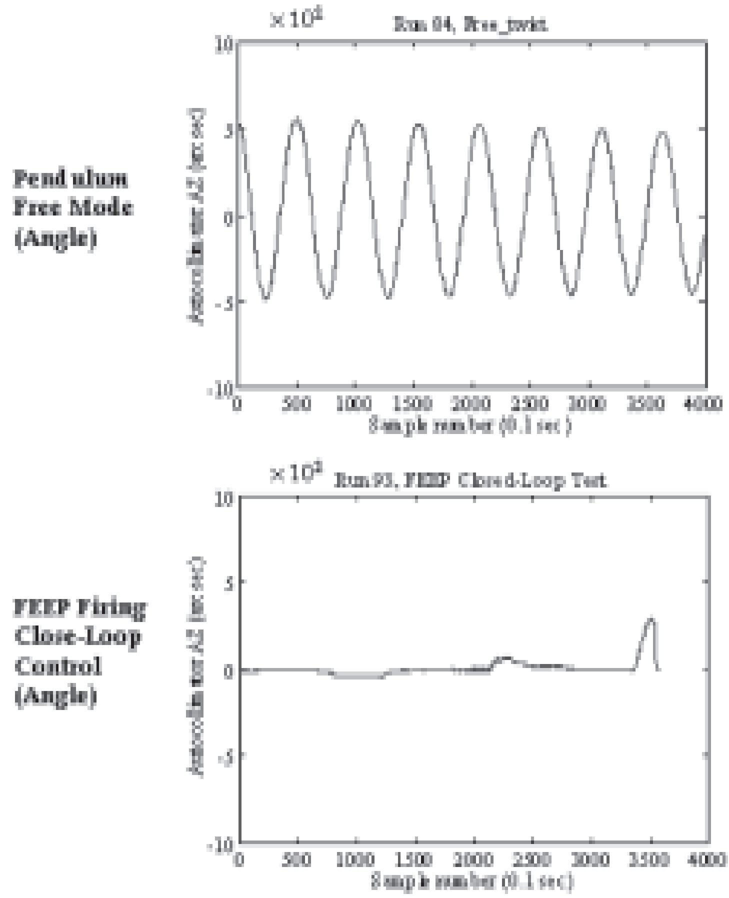

Figure 4-13. Null-Mode Performance of Micro-Newton Thrust Stand Controller

[Technical contact: Peiman Maghami]

5.0 Branch Infrastructure

5.1 Flight Dynamics Tools Maintenance

During the fiscal year, the Flight Dynamics Tools task supported institutional software maintenance and enhancement activities in the technical areas of attitude error analysis, prediction and determination; navigation, orbit prediction and determination, and error analysis; and, mission analysis, trajectory design and analysis, and maneuver planning.

In these efforts, the task provided sustaining engineering support for guidance, navigation and control (GN&C) institutional flight dynamics tools by maintaining core expertise associated with the software, provided analysis of the implementation and use of these tools, defined and conducted maintenance activities, and provided configuration management and system administration support.

As part of the this task, a survey was distributed to the user community soliciting corrections and enhancements to the Multimission Spin-Axis Stabilized Spacecraft (MSASS) and Multimission Three-Axis Stabilized Spacecraft (MTASS) software, and a report was written concerning their needs. A considerable amount of work was accomplished in documenting MSASS and MTASS algorithms and making numerous modifications and software corrections. This work was accomplished to ensure that the FDAB has the capabilities to perform the necessary analysis and resolve anomalies for current operational missions, as well as perform analysis and prepare for the support of future missions. For MSASS, the enhancements and modifications include: developing front end software to process attitude telemetry for the Space Technology 5 (ST 5) mission; accounting for spin-axis nutation to provide more accurate attitude estimation in spinning spacecraft; and providing the capability to process magnetometer data for spinning spacecraft, which will make the attitude estimation more accurate. For MTASS, the enhancements and modifications include: star identification using a pattern matching algorithm for easier star identification for missions using star trackers; and gyro calibration automation, giving a framework to enable missions using gyros to automate the sensor calibration process using ground-based batch processing and eventually onboard processing.

The task continued to support the Global Positioning System (GPS) Enhanced Orbit Determination (GEODE) and GPS Enhanced Onboard Navigation System (GEONS) maintenance effort, including investigation and correction of reported discrepancies; maintaining system documentation; maintaining software configuration and testing archives; performing integration and testing; making software updates and associated data simulation capabilities, and writing acceptance test reports; and, supporting requests for information from licensees.

[Technical contact: John Lynch]

5.2 Navigation Systems Development

An in-house navigation systems development effort has been performed by FDAB engineers to maintain and enhance major ground-based navigation systems such as the Goddard Trajectory Determination System (GTDS). Major work includes:

- Place identified systems (and versions) under software configuration control by the FDAB Lab
- Build optimal systems from different versions on the UNIX platform (these optimal systems will become official FDAB navigation systems)
- Port all FDAB ground-based navigation systems to PC platforms
- Develop user-friendly interface for PC versions of FDAB ground-based navigation systems
- Add technical and graphical capabilities to PC versions of FDAB ground-based navigation systems
- Perform research and analysis to improve performance and optimize operational use of ground-based navigation systems to support future missions (e.g., as backup systems in formation flying, in case of failure of onboard navigation systems).

The delivery of GTDS Version 2.2 was completed. Release 2.2 includes the following:

1. TLE2ELE - NORAD 2-Line Element to ELCONV format Conversion Program
2. TLE2ELE - NORAD 2-Line Element to NORADEP format Conversion Program
3. Port of the HP-UNIX Operational Release 2001.01 of GTDS to the Windows environment

The software enhancement for GTDS Release 3.1 was also completed, and a Beta version of Release 3.1 has been delivered for acceptance testing. It includes the following modifications:

1. Capability to use geopotential models up to 360x360 in size, including the complete EGM96 geopotential model.
2. Capability to use EGM96 enhanced Earth tide model
3. Capability to use central bodies other than the Earth, Moon, or Sun.

In addition, the development of a sophisticated user interface and graphics capabilities (GUI) for GTDS is in progress with the support of Code 583 software engineers. A version of this GTDS GUI that includes basic functions of ephemeris generation (EPHEM), ephemeris comparison (EPHEM COMPARE), and differential correction (DC) is planned for completion by December 31, 2003.

[Technical contacts: Son Truong, Joseph Toth]

5.3 Goddard Mission Analysis Tool (GMAT)

Numerous missions being considered at NASA GSFC propose flying a distributed system of spacecraft that coordinate activities to achieve a common goal. These missions often require careful orbit design to ensure that the collection of spacecraft provides the maximum possible science return. The mission design problem is further complicated by real-world mission constraints that are often in conflict with the science objectives. Examples of such constraints include maximum and minimum spacecraft separations, mass to orbit limitations, maximum survivable eclipse duration, and navigation and control system constraints.

The Goddard Mission Analysis Tool (GMAT) is intended to provide a software solution to such challenging mission analysis problems described above. See Figure 5-1 for a sample user interface for the GMAT system. The approach is to provide analysts with a suite of state-of-the-art numerical optimization routines and dynamics models to best address the specific problems associated with a particular mission. We are developing a suite of software tools that can be used to optimize formation configurations to maximize science return, while simultaneously satisfying real mission constraints. The system will use state-of-the-art numerical optimization techniques such as Sequential Quadratic Programming and Genetic Algorithms to provide innovative mission solutions that maximize performance metrics provided by mission scientists. While the primary objective is to address multiple spacecraft missions, the suite of tools is being designed so that it is generally applicable to all GSFC missions. This effort will enable GSFC mission analysts to provide projects with the best possible orbit design to maximize the science return of complex distributed spacecraft missions and to clarify the relationships between specific mission constraints and science performance. GMAT will also greatly decrease the amount of effort required for feasibility studies for future missions.

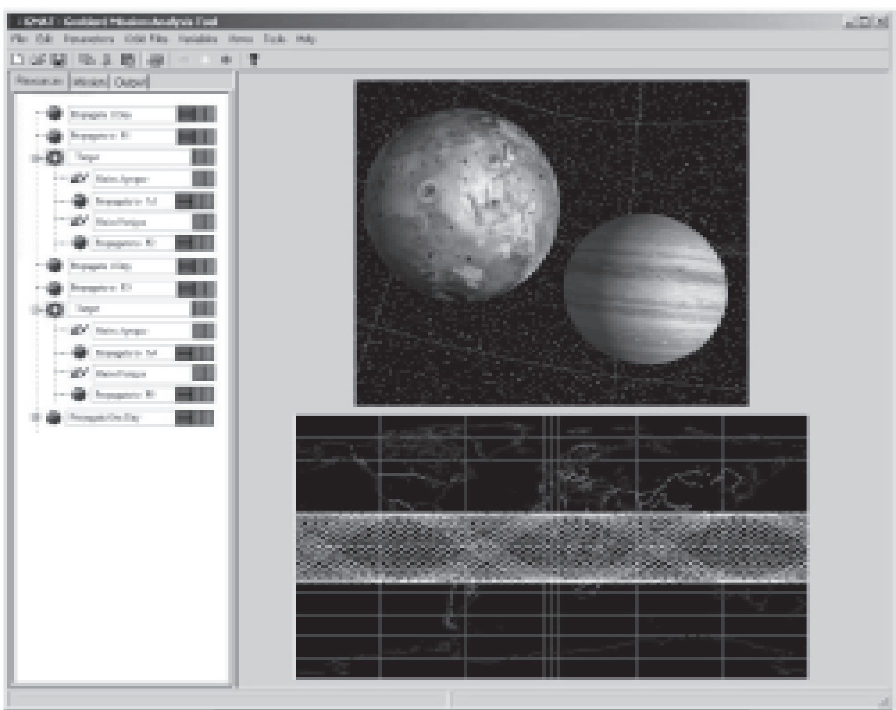

Figure 5-1. Sample User Interface for the GMAT System

The environment modelling for GMAT is to be provided by the Virtual Almanac Library (VAL). VAL is accessed through a set of "C" language style functions allowing the library to be accessed from a variety of programs. The models included in VAL include coordinate system transformations, time conversions, planetary ephemerides, spherical harmonics models, magnetosphere models, and atmospheric density models.

While working on this effort we have worked closely with the Office of Patent Counsel to ensure that the systems developed can be released under an Open Source Software Usage Agreement. Hence, one of the goals of the GMAT development effort is to produce software systems that can be shared with and modified by others in the space community.

[Technical contacts: Steven Hughes, David Folta, John Downing]

5.4 SKY2000 Star Catalog

The SKYMAP software and SKY2000 Master Catalog (MC) database are used by flight dynamics analysts to generate star catalogs used by many current (and for several future) NASA and National Oceanic and Atmospheric Administration (NOAA) space science missions. The SKY2000 MC contains a wide variety of stellar data on ~300,000 objects and is "complete" to ~ visual magnitude (Mv) 8.5 with information on many objects several magnitudes fainter. The SKY2000 MC database was initially constructed using the best information available from a variety of published, specialized star catalogs. A hierarchy of data selection criteria and a rigorous catalog object identification cross-referencing approach for the SKY2000 MC was established based on individual star catalog characteristics, so that only the best data for each stellar object were included in the MC.

The SKYMAP software suite is used to generate subsets of the SKY2000 MC to meet a variety of user star catalog requirements and for MC database analysis and maintenance. Star catalogs may be required by the onboard flight software (FSW) for attitude determination and/or for ground-based attitude determination systems. Star catalogs may also be required for NASA spacecraft science instrument planning/operational support, and the MC and subsets are regularly used by members of the astronomy community and in COTS software tools used for planning ground-based observations.

A new magnitude reference system was established for the SKY2000 MC using in-situ observations obtained from the Rossi X-Ray Timing Explorer (R-XTE) Ball Aerospace CT-601 Charge-Coupled Device Star Tracker(s) (CCDST). The RXTE magnitude observations are now included in a new MC magnitude passband data field tailored for wide-band, red/infrared sensitive CCD-type instruments. The CT-6xx magnitude observations provide the best data for generating accurate instrumental magnitude predictions for CCDSTs or other sensors with similar spectral response characteristics. The data from ~1 million separate RXTE CCDST observations from the RXTE science archive over ~6 years were reduced and combined into about 15,200 means for individual observed stars. This analysis also provides information not previously available on stellar variability in the Ball CT-6xx star tracker passband. The new data provide observed values for approximately 75% of the stars detectable by the CT-6xx (or similar) star trackers, and can be used in magnitude predictions for SKYMAP catalogs to be used by existing and future missions.

Accurate, complete star catalogs containing at least star positions, star identifiers, and predicted instrumental magnitudes are necessary for spacecraft attitude determination using star trackers, which do not contain internal star catalogs. Such catalogs are also used by autonomous star trackers, but are internal to the sensor. A variety of additional physical parameters for each star entry in the MC are also available and can be included in the standard Multi-Mission Spacecraft (MMS) Run Catalog produced by MMSCAT or in custom star catalogs (http://mmfd.gsfc.nasa.gov/index.htm). The MMSCAT magnitude correction/near-neighbor handling algorithms were modified to improve the accuracy of predicted sensor passband magnitudes and to reduce the time required for catalog generation by incorporating a magnitude correction "post-processing" step into the main program.

The Attitude and Orbit Models (AOMS) task personnel have also provided consultation and star catalog generation support for several missions this year including two updates to the RXTE onboard star catalog, a preliminary Active Pixel Sensor (APS) Star Tracker catalog, SDO analysis star catalog, star catalog/star identification consultation for Gravity Probe B, and star catalog consultation for Swift.

Figure 5-2 shows the magnitude residuals for RXTE (RXTE observed minus MMSCAT predicted). The same set of residuals is shown for two versions of MMSCAT. The light points (unfilled diamonds) are for the pre-2002 version of MMSCAT, while the dark points (filled diamonds) are for the 2003 version of MMSCAT, which incorporates the changes and improvements from FY2002 and FY2003. Reduction in scatter and outliers is due to revision of near-neighbor handling and magnitude blending algorithms.

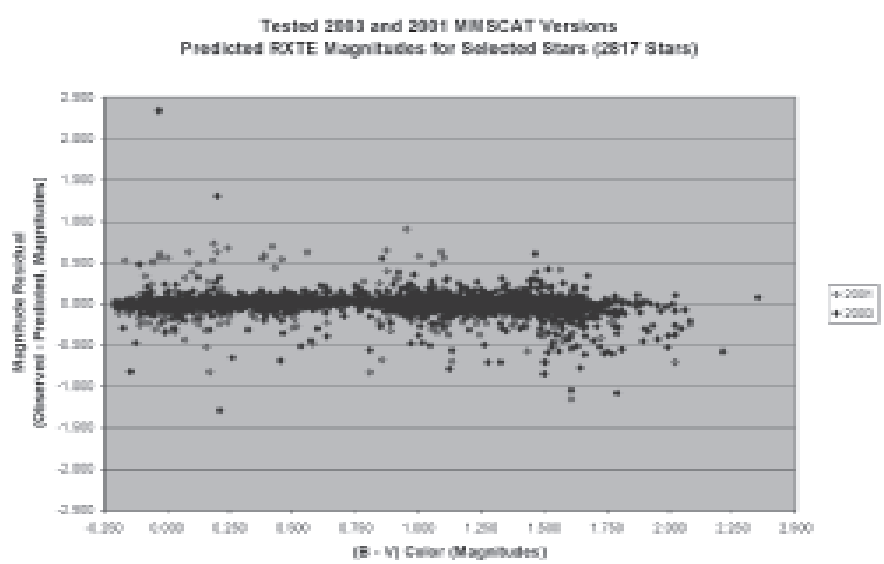

Figure 5-2. MMSCAT Improvements in Solar Magnitude Estimates

Figure 5-3 is a plot of measured magnitudes acquired by the CCDST's onboard RXTE versus time for the Mira variable star R Aquila. The amplitude of variation in the CCDST passband is not predictable from the amplitude of variation in the V or B passbands. Hence, CCDST data are needed to determine how much a particular star varies in brightness in the CCDST passband. This information is very useful in assessing a particular star for use by a mission, but it can also affect near-neighbor stars that might be considered for use by a mission (if one star in a blended pair varies in brightness, the center-of-light position of the pair changes over time).

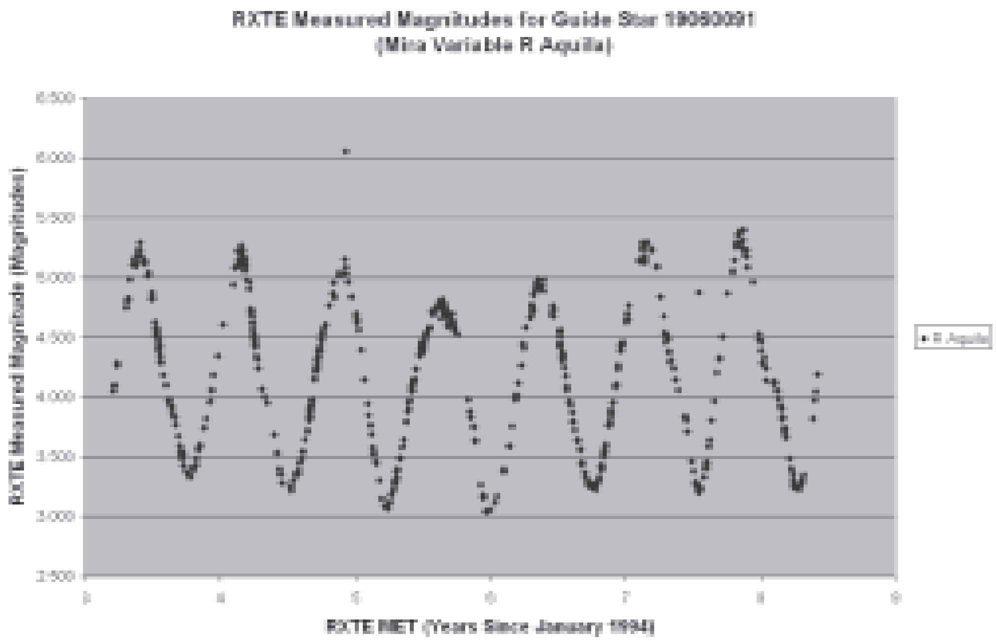

Figure 5-3. Reduction of RXTE Star Tracker Data (Variable Star R Aquilla)

Figure 5-4 shows the individual means, post data reduction, for identified stars in the RXTE CCDST data. This is a plot of the sky coverage of those positions. The gap roughly in the center corresponds to one of the Galactic poles; the gap near the lower right-hand edge corresponds to the other pole. The U-shaped band of denser coverage corresponds to the plane of the Galaxy. RXTE's ST1 boresight points in the same direction as the science instruments, and by itself would only acquire stars near the science targets. However, the offset of the ST2 boresight, which varies in roll around the ST1 boresight, gives additional sky coverage. Over the course of the mission, the science target list has changed gradually as well.

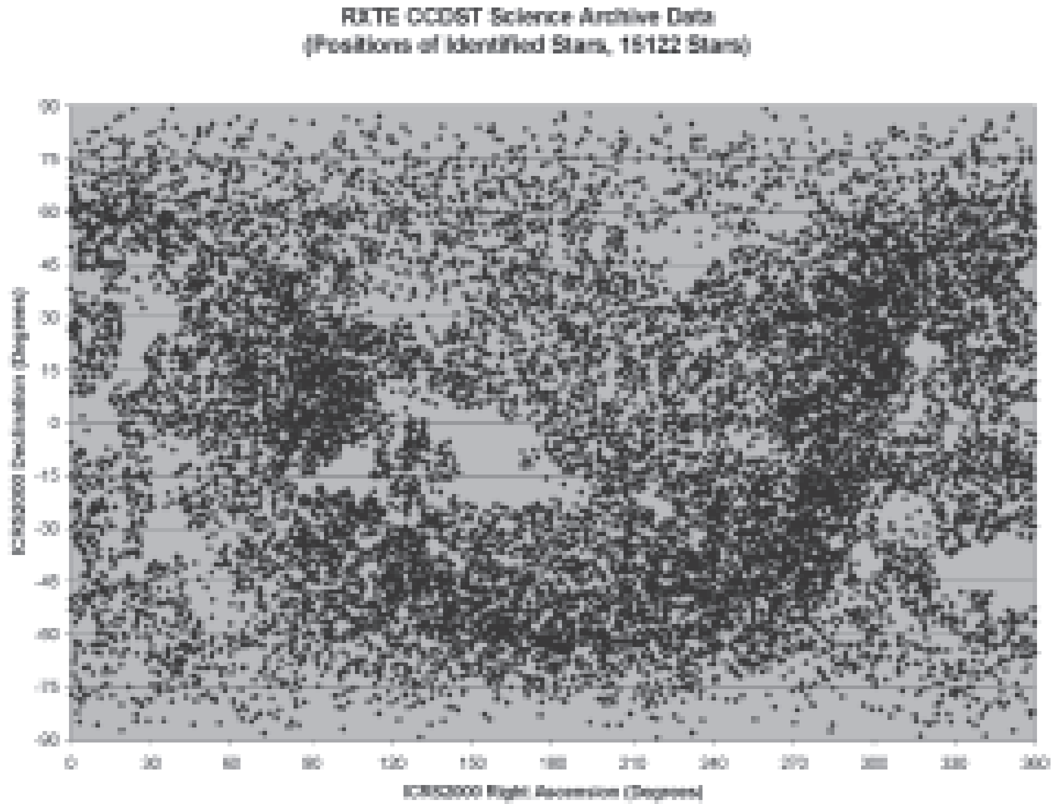

Figure 5-4. Reduction of RXTE Star Tracker Data (Sky Coverage)

[Technical contact: David Tracewell]

5.5 Solar Flux Predictions

Between Oct 2002 and Sept 2003, it appeared that solar cycle #23 was winding down in a fairly well-predicted manner, with the next minimum solar activity expected in 2007. Under contract to the FDAB, Dr. Kenneth Schatten of ai solutions, Inc. updated the solar flux predictions twice during the year, and wrote a paper summarizing the results for the October 2003 FDAB-sponsored Flight Mechanics Symposium. Dr. Schatten and the FDAB were pleased that the actual activity had matched the overall trend as predicted at the beginning of Cycle #23 in 1997 (see Figure 5-5 from his FMS paper 2003-19. This gave credence to the solar dynamo theory used to generate the Schatten solar flux predictions.

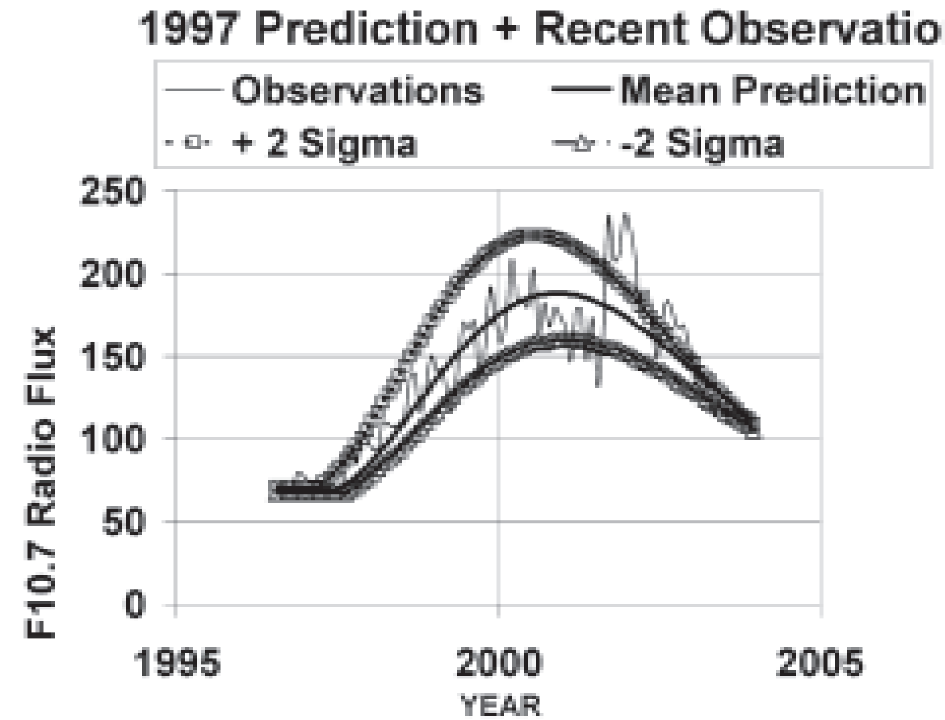

Figure 5-5. Predicted and Observed Solar Flux

All seemed to be going as planned, and low Earth orbiting (LEO) satellite operations teams were expecting a reduction in the frequency and magnitude of drag makeup maneuvers for the next few years. However, in mid-October the Sun became extremely active with several huge solar flares erupting, creating the most spectacular show ever witnessed by modern man. The daily solar activity peaked at least twice in October at unheard of values. Solar activity has continued to be frequent and extreme, with the Sun completing its polarization 'flip' in November 2003. The FDAB's expert Dr. Kenneth Schatten has been busy updating the solar flux predictions to account for this unexpected activity. The Schatten predicts are used not only by the FDAB, the Flight Dynamics Facility at GSFC but also by many other organizations around the world. While the most noticeable effects of increased solar activity are the increased atmospheric drag and therefore the more rapid decrease in satellite orbit altitude, radio frequency interferences have also been detected, as well as spectacular auroral activity in the Earth's polar zones. Next year's end-of-year report will cover this late-breaking solar activity news.

[Technical contact: Karen Richon]

5.6 Flight Dynamics Lab

The Flight Dynamics (FD) Lab, located in Building 11, provided system file server support and application license managing for the MESA Division. The FD Lab houses the web servers for the FDAB web page and the flight dynamics on-line tools. Phase 1 development of the Attitude Component Database was completed and delivered. This database will allow MESA engineers access to a comprehensive database of spacecraft attitude component parts and their specifications. Initial user testing was begun and the Phase 1 database is expected to be available to MESA engineers sometime in the last quarter of calendar year 2003. Phase 2 of the database development is expected to begin sometime in fiscal year 2004.

The FDAB web page was updated and used for online registration for the 2003 Flight Mechanics Symposium. Additional updates were done to bring the FDAB web page into compliance with NASA regulations in the areas of accessibility and security.

[Technical contact: Susan Hoge]

5.7 Flight Dynamics Facility (FDF) Support

The FDAB assisted the Mission Services Program Office in planning a Flight Dynamics Facility backup in Building 13. This support included system engineering and planning, schedule review, hardware procurement, and operations planning. The backup facility is scheduled to be operational in FY2004.

Additional support to the FDF was provided in the area of TDRS close approach management. Consultative support for maneuver strategies was provided to assist in the determination of the best approach to close approach avoidance with neighboring spacecraft.

The FDAB was the lead organization for writing the statement of work for the Mission Operations and Mission Services (MOMS) work package that will become the contract for the flight dynamics support in January 2004. The FDAB will be responsible for managing the Flight Dynamics Facility under the MOMS work package and will be the point of contact for flight dynamics services under MOMS.

[Technical contact: Sue Hoge]

6.0 Interagency Activities

6.1 TIMED Mishap Investigation Board

http://www.timed.jhuapl.edu/

TIMED was launched on December 7, 2001. Due to several early in-flight anomalies, a Mishap Investigation Board (MIB) was formed. The MIB investigated the anomalies in spring 2002. The first MIB report to the Goddard Program Management Council (GPMC) was in May 2002, with a final presentation to the GPMC in August 2002. The MIB Final Report was released in September 2002. Following the release of the report, there were implementation discussions with Code 300 and the Johns Hopkins University Applied Physics Laboratory (APL) held in October 2002. The Sun Earth Connection team and APL made several presentations to the GPMC in late 2002 and spring 2003.

The TIMED MIB gave a presentation to GPMC documenting our assessment of APL and NASA's responses to the report in June 2003. At that point, the job of the TIMED MIB was over. A summary presentation of the spacecraft, the anomalies, and the MIB process was also given to FDAB personnel in April 2003. As of September 17, 2003, TIMED had been in orbit 650 days and is successfully performing its mission.

[Technical contact: Stephen Andrews]

6.2 Comet Nucleus Tour (CONTOUR) Mishap Investigation Board

http://www.contour2002.org/

On August 15, 2002, the CONTOUR spacecraft (see Figure 6-1) suffered a catastrophic failure during the firing of the solid rocket motor. A NASA Headquarters Class A Mishap Investigation Board (MIB), headed by the NASA Chief Engineer, was quickly established to find the root cause or causes of the mission failure. The CONTOUR MIB requested that the FDAB assign a senior GN&C expert with a specialty in spacecraft dynamics to the team.

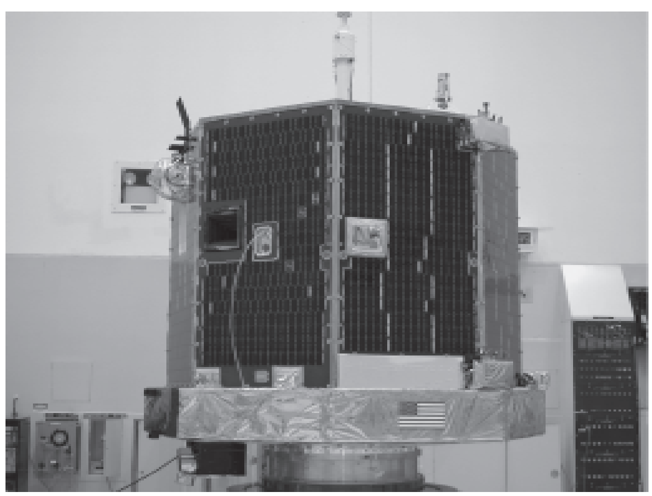

Figure 6-1. CONTOUR Spacecraft

There was no telemetry from the spacecraft during the motor firing. Therefore, the MIB had to rely on other resources for in-flight data. The FDAB supported the MIB by assigning additional personnel to study the slim possibility of the event being captured with a star tracker of a nearby spacecraft. The study involved hundreds of spacecraft. While no spacecraft star tracker-to-CONTOUR geometry worked out, the MIB was very appreciative of the effort. FDAB personnel also formally reviewed the pre solid rocket motor firing Doppler data. This review of the data verified the spin and nutation frequency information and became critical information for the CONTOUR MIB.

Due to the lack of data, a definitive cause could not be found. The solid rocket motor was thoroughly investigated by experts from across the country. Manufacturing records, travel logs and x-ray examinations were all reviewed. Simulations were developed that modeled the in-orbit environment as well as the burning characteristics of the motor. The track record showed that there had not been a motor failure since the 1960's with a different nozzle material.

There was evidence of higher than expected plume heating on the spacecraft near the deeply embedded motor nozzle. This plume heating was high enough to melt a nearby low gain antenna. The temperature uncertainties of objects near the nozzle, due to plume heating modeling, typically require a shielding design that is fairly robust. Objects do not have to reach their melting point, but only reach a yielding point, when subjected to the 6-g thrusting environment. Objects separating from a spinning spacecraft will result in a dynamic imbalance. The FDAB was able to show that a dynamic imbalance of the spinning spacecraft with a firing thruster can produce extremely high acceleration loading within a few seconds. Therefore, it is the opinion of the CONTOUR MIB that the most likely cause of the failure was due to plume heating.

[Technical contact: David Mangus]

6.3 Solar-Terrestrial Relations Observatory (STEREO) Consultation

http://stereo.jhuapl.edu/

NASA Goddard Space Flight Center's Solar Terrestrial Probes Program Office in Greenbelt, Md., manages the STEREO mission, instruments and its science center. The Johns Hopkins University Applied Physics Laboratory, in Laurel, Md., is designing, building and operating the twin observatories for NASA during the two-year mission.

The STEREO Mission uses a pair of spacecraft to measure three-dimensional coronal mass ejections from the Sun and the heliosphere, and will use the data to increase the reliability for predicting space weather alerts for Earth directed coronal mass ejections. The pointing knowledge requirement is 0.1 arcseconds, and a November 2005 launch is planned.

FDAB personnel have served as panel members at a number of reviews, some project-mandated, and others internal to APL. At these reviews, detailed technical designs were discussed, criticized and subjected to scrutiny to assure conformance with NASA and GSFC standards. Some FDAB-initiated actions are detailed below.

STEREO Critical Design Peer Review of the STEREO G&C Subsystem

- Verify adequate stability margins with reduced 0.1% structural damping
- Develop G&C pointing performance metrics. The APL response is a high qualitymathematically consistent set of pointing requirements (documented in “Definitions, Metrics, and Algorithms for Displacement, Jitter, and Stability,” by Mark Pittelkau, presented at the GSFC 2003 Flight Mechanics Symposium)
- Minimize gyro hardware bandwidth (consistent with phase delay) to lessen structural jitter input to control system

STEREO Observatory Critical Design Review

- Require a presentation of the System Fault /Autonomy system to FDAB personnel
- Test plans to be made available to FDAB Personnel to confirm Safe Mode design
- Explanation of changes to Teldix Reaction Wheels to meet EMC requirements
- FDAB to review all G&C phasing test plans

STEREO Earth Acquisition Mode Peer Review

- Concern with the testing and use of autonomous thrusters in Earth Acquisition Mode, and the reliance of a self-diagnostic check for fault detection of the Inertial Measurement Unit (IMU).
- Re-examine minimum-time slew mode with a view towards decreasing the torque bang/bang effects on the wheels. APL corrected an implementation error and improved the controller response.

[Technical contact: Michael Femiano]

6.4 NASA Technical Standards Program

http://www.ccsds.org/
http://standards.gsfc.nasa.gov/

The FDAB supports the NASA Technical Standards Program by contributing to the work of the GSFC standards program, the NASA Data Standards Steering Council (DSSC), and the Consultative Committee for Space Data Systems (CCSDS). The GSFC standards program aims to expand the scope of best practices, and to develop an agency-endorsed database of preferred technical standards for NASA. The DSSC is the hub of the NASA Data Systems Standards Program and is sponsored by NASA Headquarters.

The CCSDS is an international organization of space agencies interested in mutually developing standard data handling techniques, to reduce cost, risk and development time, and to promote enhanced interoperability and cross-support. CCSDS was reorganized in 2003; GSFC personnel participated in the definition of the program scope and the charters for the new technical working groups.

The CCSDS navigation workshops were conducted at the Wyndham Greenspoint Hotel, Houston, Texas, in October 2002, and The Netherlands European Space Agency (ESA) facility in April 2003. The navigation working group completed another detailed review of the Orbit Data Message (ODM) Red Book, to separate syntax and semantics and to incorporate use of extensible markup language (XML). This reorganization of the document provides ASCII and XML transport options of the orbit parameters and ephemeris messages. In addition, the working group continued discussions of tracking data requirements and writing operational characteristics of tracking data support and tracking data descriptions, as a first step for producing a tracking data standard; completed writing requirements on spacecraft identifications, to be delivered to the CCSDS Space Assigned Numbers Authority (SANA) for action; and, developed a description of navigation timing issues to be provided to the new Time Synchronization Architecture Working Group. The navigation working group also interfaces with CCSDS experts in the areas of space link extension (SLE), XML and timing. Future work will include completing the ODM certification as a formal standard and developing standards for tracking and attitude data exchange.

[Technical contact: Felipe Flores-Amaya]

7.0 Employee Development Activities

7.1 New Employee Profiles

During FY2003, the Flight Dynamics Analysis Branch welcomed two new employees:

Kuo-Chia (Alice) Liu joined the Flight Dynamics Analysis Branch on April 7, 2003. Alice received her B.S. and M.S. degrees in Aerospace Engineering from the University of Maryland at College Park. Her graduate work at Maryland focused on space robotics and advanced controls research, culminating in her Master's thesis entitled "Adaptive Friction Compensation in Robotic Manipulators Using Multiresolution Neural Networks." She continued her graduate career at the Massachusetts Institute of Technology, where she earned a doctorate degree in Spring 2003. While at MIT, she worked on a range of projects including dynamic analysis for the Terrestrial Planet Finder (TPF) mission, controller designs for SPHERES (a formation flying testbed), and attitude/pointing control algorithms for ARGOS (Golay 3 telescope testbed). Her studies at MIT were funded by a JPL Michelson graduate fellowship, and her dissertation research focused on developing control algorithms for interferometer systems. The title of her dissertation was "Stochastic Performance Analysis and Staged Control System Designs for Space Based Interferometers." Alice is currently working on the modeling, control design, and performance analysis aspects of the Solar Dynamic Observatory (SDO) and the Laser Interferometer Space Antenna (LISA). She is also looking forward to being a part of the growing interferometer effort at Goddard.

Rivers Lamb returned to the Flight Dynamics Analysis Branch on August 25, 2003. He first started working in the Branch as a Co-op in January 2001 and earned his B.S. in Aerospace Engineering from Virginia Polytechnic Institute and Statue University (Virginia Tech) in May 2003. Rivers is currently working to understand the relative motion of the three ST-5 spacecraft for his Professional Intern Program (PIP) I project. In the meantime, he is supporting SDO mission design and TRMM de-orbit planning.

7.2 Professional Intern Program (PIP)

The Professional Intern Program (PIP) is a Goddard developmental program for entry-level scientists, engineers, and administrative professionals. Within the FDAB, it is an important development program for new engineers, designed to acquaint them with NASA and GSFC missions and operations, integrate them into the workforce as quickly as possible, and prepare them for more complex and responsible duties that they can perform with increasing independence. There are two levels of participation within the program. Employees entering with a B.S. degree begin at Level I and graduate to Level II following completion of Level I requirements and their first promotion. New employees entering Goddard with an M.S. degree begin at Level II. Required program activities include the establishment of a mentor relationship with an experienced staff member, various orientation activities, formal and on-the-job training, and completion of a PIP project, which the intern describes in a written report and oral presentation given in Levels I and II to a panel of evaluators. During the past year, five PIP projects were completed and presented. A description of each of these PIP projects (prepared by each intern) is given below.

PIP Level II Project: Constellation Control Using Ballistic-Coefficient Changes (Anne DeLion)

This project examined the use of drag-differencing between spacecraft for constellation control. The studied constellation was based on the ST-5 mission and consists of three small identical satellites deployed via phasing maneuvers into a ‘string of pearls’ configuration in a highly elliptical orbit. The goal of this project was to maintain a one-hour mean-local-time separation between the spacecraft at apogee by halting the drift caused by the deployment phasing; this separation would be about orbital apogee only and would occur within 45 days of deployment.

The analysis used a proportional-derivative (PD) controller to implement the control scheme. The first part of the analysis examined whether it was possible to stop the deployment drift using only spacecraft drag in the nominal ST-5 spacecraft configuration. Analysis showed that, although the ST-5 constellation in its current form could be affected by drag differences, there was not enough ballistic-coefficient difference between the spacecraft to meet the 45-day goal of the project. The second part of the analysis found what changes would need to be made to the ST-5 configuration in order to achieve the project goal. It was shown that if changes were made to either the ST-5 deployment scenario or the ST-5 spacecraft physical properties, then drag-differencing control could be applied to meet this project’s goal. The control output was found to be affected by both lunar and solar perturbations, which means that it was also epoch dependent.

(Anne DeLion has been a full-time Goddard employee since July 2001. Prior to that time, she was a Co-op student within the Branch. She received her B.S. degree in Aerospace Engineering from Purdue University.)

PIP Level II Project: Multi-mode Simulation Development for ST7 (Oscar Hsu)

The Space Technology 7 (ST-7) Disturbance Reduction System (DRS) is a mission within the New Millennium Program with a goal of testing two advanced technologies, Gravitational Reference Sensor (GRS) and micronewton colloidal thrusters. ST-7 is scheduled for a 2007 launch aboard ESA’s SMART-2 spacecraft on a drift-away trajectory towards the Sun-Earth L1 Lagrange point. Some of the technical objectives of this mission are to validate that a test mass can be made to follow a trajectory determined by gravitational forces only within $3x10^{-14}$ x $(1+(f/3 \text{ mHz})^2)$ m/($s^2\sqrt{\text{Hz}}$), and validate spacecraft position control to an accuracy of less than 10 nm/$\sqrt{\text{Hz}}$ within the measurement band of 1-30 mHz. Therefore, a number of controllers were developed to control the spacecraft in order to meet the mission objective. The purpose of this PIP Level II project was to develop an 18-degree-of-freedom (18-DOF) nonlinear multi-mode ST-7 Simulink simulation for use in controller validation and mode transition analysis.

In the process of developing the multi-mode simulation, a single mode 18-DOF nonlinear simulation was developed and validated against a linear model. The time history results were compared between the two simulations and the results were in good agreement. In addition, simulations were run with gains at 95 and 105% of the predicted gain margin values for the 60 inputs and outputs to the controller. The time histories showed the expected results and the measured instability frequency was within 3% of the predicted values. Therefore, it was concluded that the non-linear simulation was valid and could be used as a baseline for the multi-mode simulation development.

The culmination of the project resulted in an 18-DOF multi-mode nonlinear ST-7 simulation that was able to transition from its initial operational mode at spacecraft hand-over to the full drag-free science mode. The final model will be used as a reference model for use in VirtualSat Pro™ (the Hammers Company), which will be used for hardware-in-the-loop and software testing.

(Oscar Hsu has been a Goddard employee since September 2002. He received his B.S. and M.S. degrees in Aerospace Engineering from the University of Maryland.)

PIP Level II Project: GPS Navigation in a High Drag Environment: Applications to Global Precipitation Measurement and Drag-Free Control Concepts (Bo Naasz)

The GPM mission (specifically, the onboard radiometer) requires the spacecraft to maintain its orbital semi-major axis to within 1 km, since less calibration of science data is required if most of the data is taken at relatively similar altitudes. This orbit maintenance will be accomplished on GPM using onboard navigation using the Global Positioning System (GPS) and the New Millennium Program's (NMP) Autonomous Onboard Formation Flying Software (AutoCON) to perform an orbit raising maneuver once every few days. The frequency of these maneuvers will vary throughout the mission as a function of solar flux, ranging from about one maneuver per week to one maneuver per day.

The heritage of the AutoCON software, and the parallels between the Earth Observing-1 (EO-1) formation flying orbit and the GPM autonomous drag compensation concept make a slightly modified version of AutoCON an excellent fit for GPM. Just as EO-1 autonomously maneuvers to remain within a control box defined relative to Landsat-7, GPM can autonomously maneuver to remain within a semi-major axis – eccentricity control box defined by the science mission requirements.

The primary goal of this work was to demonstrate the use of GPS-based onboard navigation and control to meet the orbital maintenance requirements of GPM. This task was separated into two major categories: 1) implementation of onboard navigation using the GPS Enhanced Onboard Navigation System (GEONS); and, 2) development and implementation of a one-apogee-burn control strategy for GPM. Figure 7-1 illustrates a sample application of the one-apogee-burn control strategy for GPM.

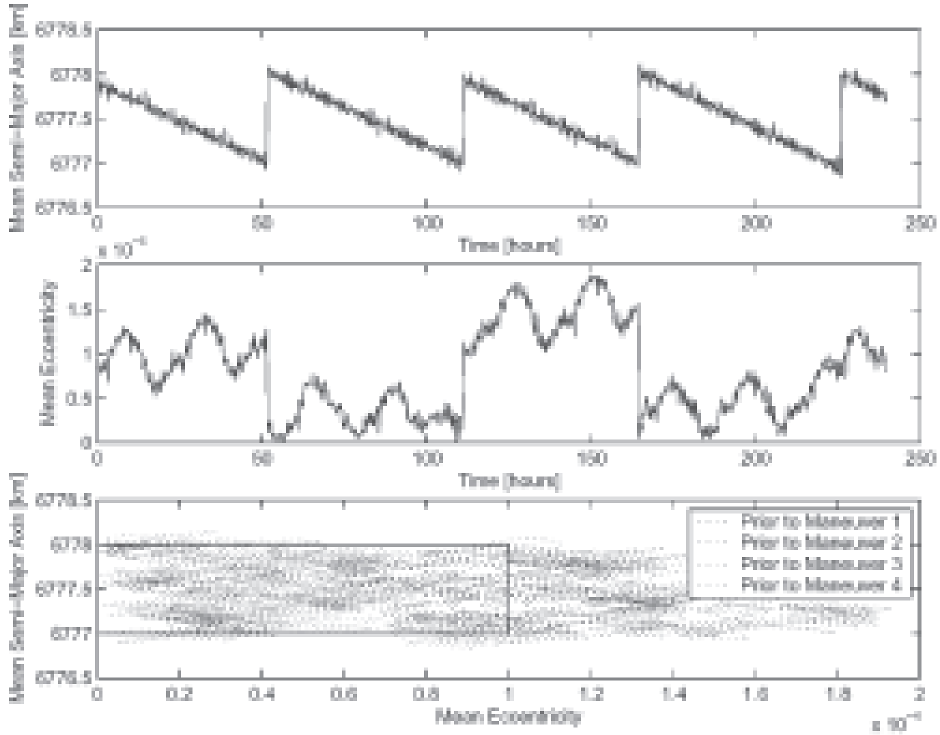

Figure 7-1. Sample Application of the One-Apogee Burn Control Strategy for GPM

The secondary goal of this work was to determine the effect of drag-free control on GPS-based navigation accuracy. This goal was related to the primary goal in that it allows us to explore the effects of drag, and other navigation error sources, on the navigation system. The insight gained from this work serves directly to improve our understanding of GPS-based navigation for any spacecraft in an elevated drag regime.

(Bo Naasz has been a Goddard employee since July 2002. He received his B.S. and M.S. degrees in Aerospace Engineering from Virginia Polytechnic Institute and State University.)

PIP Level II Project: Automating Magnetometer Calibration for TRMM (John M. Van Eepoel)

The TRMM spacecraft has been in operation since 1995 and has provided a wealth of science data about rainfall and precipitation, and has allowed scientists to improve weather forecast models. The benefits of the mission far outweigh the costs to operate the spacecraft, but nonetheless, measures have been taken to reduce the operational costs. One approach that is being pursued is the re-engineering of the attitude estimation software, discussed previously in Section 2.2.6.

TRMM has a suite of sensors consisting of two digital sun sensors, two magnetometers, three two-axis gyroscopes, an Earth sensor, and coarse sun sensors. The Earth sensor is no longer used operationally due to the orbit of TRMM being boosted to a higher altitude in August 2001. As a result, the mission became more reliant on the magnetometers as attitude sensors, and because of this, more accurate measurements from the magnetometers were required. This project aimed to improve the attitude estimation operations and performance by automating calibration of the magnetometers.

In order to obtain more accurate measurements, the sensor is calibrated to remove misalignment, scale factor, bias, and torquer bar coupling errors. This was originally performed in 2001; however, the results degraded over time. In order to consistently obtain the best results from the magnetometer, it is necessary to calibrate them on a regular basis. This is a time consuming process, so it was deemed that automation should be pursued to improve the process.

The calibration automation leveraged a pre-existing calibration algorithm in the attitude estimation software package, the Multi-mission Three Axis Stabilized Spacecraft (MTASS) System, which is already being used for TRMM attitude operations. The calibration automation performs several steps:

1. Determines if the calibration is necessary
2. Pre-processes the data to make sure it is proper for the calibration
3. Performs the calibration
4. Checks the results, and if they do not pass a quality test, then the process returns to Step 2

In Step 1, a simple warning system was implemented that notifies the user, via email, if the calibration is drifting off and will be necessary soon, or if the calibration is poor and the magnetometers are being calibrated. This is similar to a "yellow" and a "red" warning, respectively. In addition to the calibration automation, the attitude estimation process was also automated, which will benefit TRMM attitude operations directly. This automation has been successfully implemented for TRMM and favorable results have been obtained. The next steps are to let the automation run in the TRMM MOC over an extended period of time and collect and analyze the results over time. It is not currently planned to use the results operationally.

(John VanEepoel has been a Goddard employee since September 2002. He received his B.S. from the University of Maryland in 2000 and his S.M. from MIT in 2002, both in Aerospace Engineering.)

PIP Level II Project: Drag-Free Control of Spacecraft in Low Earth Orbit (Melissa Vess)

A PIP Level II project, entitled "Drag-Free Control of Spacecraft in Low Earth Orbit," was successfully completed on January 9, 2003. The goal of the project was to look at the feasibility of drag-free control as a means of continuous and autonomous orbit correction for spacecraft in low earth orbit (LEO). Atmospheric drag causes the greatest uncertainty in the spacecraft equations of motion for missions in LEO. The continuously varying atmospheric density levels require increased spacecraft tracking to accurately predict spacecraft location. In addition, periodic propulsive maneuvers must be designed and performed to counteract the effects of drag on the spacecraft orbit. If atmospheric drag effects can be continuously and autonomously counteracted through the use of a drag-free control system composed of a small proof mass, sensors, and thrusters, those effects will essentially be eliminated from the spacecraft equations of motion. The main perturbations on the spacecraft will then be those due to the Earth's gravitational field, which are easily predicted.

The project was broken down into two main parts. The first part looked at the feasibility of continuous drag compensation from a fuel aspect. A combination of Matlab and Satellite Tool Kit (STK) were used to determine the fuel, measured in cumulative ΔV, required to perform orbit-raising maneuvers on various spacecraft at various altitudes. At first, maneuvers were performed every four weeks (periodic orbit raising maneuvers), and the amount of time between orbit raising maneuvers was gradually decreased until maneuvers were performed every hour (continuous drag compensation). The data gathered from this simulation showed that continuous drag compensation never required more ΔV than the periodic maneuvers, and in some cases showed significant savings in ΔV cost.

For the second part of the project, Simulink was used to create a simulated drag-free control system. This part of the project was intended to show that the drag-free control system would work on a simulated spacecraft. The simulation was also used to investigate the effects of offsetting the proof mass from the spacecraft center-of-mass. The results of the simulations showed that the drag-free control concept is feasible, especially when the proof mass is located close to the spacecraft center-of-mass. As the proof mass is moved away from the center-of-mass in either the radial or normal direction, the ΔV cost of the drag-free control increases. It becomes more expensive to compensate for the offset proof mass than it does to remove drag. If the proof mass is offset in the velocity direction, there is minimal effect on ΔV cost.

(Missie Vess has been a Goddard employee since July 2001. She received her B.S. degree in Mechanical Engineering from the University of Maryland. She is currently pursuing a M.S. degree in Aerospace Engineering from the University of Maryland.)

7.3 Cooperative Education (Co-op) Program

The Cooperative Education Program is an important link in the educational process that integrates college level academic study with full-time meaningful work experience. This is achieved through a working agreement between GSFC and a number of academic institutions. This agreement allows the students, through study and work experience, to enhance their academic knowledge, personal development, and professional preparation. Additionally, Co-op employees earn income that is based on the level of education and work experience they have attained. The FDAB fully supports the Goddard Co-op Program and many of its full-time employees were former Co-ops. In FY 2003, two Co-ops worked in the Branch. Given below are descriptions of their work experience.

Aron Cooper (University of Minnesota & Massachusetts Institute of Technology)
The primary project I worked on during my two-month tour of duty this past summer was the verification of the rhumb line precession maneuver for the ST-5 mission. The concentration of this work was to use General Maneuver (GMAN) program to verify the algorithms developed by James Morrissey for analyzing the precession maneuver. One of the ideas of the project was to use the capability of GMAN to model a cold gas

propulsion system, since ST-5 has such a system. As it turned out, this capability was not maintained during subsequent revisions of the program due to an apparent lack of demand for it. I was still able to move forward on the project by modeling the thruster force output during the course of a maneuver and not the entire propulsion system, i.e., tank pressure, fuel density, mass usage, etc. The results from both programs were within ten percent of one another for a variety of test cases, thus we concluded that Mr. Morrissey's algorithms were indeed valid. My mentor for this project was Mark Woodard; however, I also worked extensively with Robert DeFazio and consulted with Dr. Michael Rhee of the Propulsion Systems Branch.

Leigh Janes (Purdue University)
My fifth Co-op tour, from January to May 2003, was spent working on two tasks. The first project that I worked on was a swath study for a mission called Water Cycle Mission (WCM), which needed some preliminary orbit analysis. My task was to answer the question: What does it take to get complete coverage of the Earth in 3 hours? The approach I took was to assume a Sun-synchronous orbit and look at various altitude and half-angle combinations. I examined the problem for three different half-angles and used Satellite Tool Kit (STK) to produce the ground tracks for the satellites that allowed me to find complete coverage of the Earth.

The second project that I worked on was modeling a maneuver profile for Solar Dynamics Observatory (SDO) mission. I modeled burns from geosynchronous transfer orbit (GTO) to geosynchronous orbit. I used the GMAN Program to model the ascent burns and examine ground station coverage during ascent. I also modeled east-west station keeping burns. This task built on work that I had completed during my fourth Co-op tour.

7.4 The Professional Development Program (PDP)

http://nasapeople.nasa.gov/ldp/
http://www.hq.nasa.gov/office/codea/codeae/
http://mars.jpl.nasa.gov/mer/
http://sse.jpl.nasa.gov/missions/ast_missns/ast-dawn.html

The Professional Development Program (PDP) was designed to broaden the participants' knowledge and understanding of NASA and encourage the development of their leadership skills through a combination of expanded work experiences and formal training. Participants in the program are competitively selected at the Center and Agency level and identify developmental work assignments away from their home centers. Benefits include learning new job skills, being exposed to new areas of NASA and senior NASA officials, and participating in a variety of developmental activities.

Dr. James O'Donnell, a senior Aerospace Engineer in the Flight Dynamics Analysis Branch, returned to Goddard on September 3, 2003, after spending a year in the PDP. His primary work assignment was in the Office of the Chief Engineer at NASA Headquarters, where he participated in high-level meetings of the Agency Program Management Council, helped to write a new Functional Leadership Plan for the Chief Engineer's Office, and served as an advisor to the CONTOUR Mishap Investigation Board. Dr. O'Donnell's collateral PDP assignment was in the Office of Safety and Mission Success

(OSMS) at the Jet Propulsion Laboratory (JPL), where he participated in Red and Blue Team activities investigating test failures and anomalies with the Mars Exploration Rovers (now known as *Spirit* and *Opportunity*) as a part of the effort leading up to their successful launches in June 2003. He also worked with the Project Systems Engineer and Mission Assurance Manager of the Dawn Project to prepare the Dawn Risk Management Plan, and began the process of configuring the project's risk tracking tool. Finally, Dr. O'Donnell participated in the OSMS Monthly Reviews, giving him an overview of the 41 projects on which JPL is working.

Note: The 2002-2003 PDP class was the final one. The program has been revamped and is now known as the NASA Leadership Development Program (LDP). The first year of the LDP is very similar to the last year of the PDP, but the program will most likely continue to evolve. The mission statement of the LDP is: "To develop effective leaders who align with NASA's mission and vision of the future, and who are dedicated to creating measurable results that matter to the American people."

[Technical contact: James O'Donnell]

7.5 Flight Dynamics Seminars

Beginning in the spring of 2003, the Branch sponsored a weekly series of in-house seminars. The purpose of these seminars was to present topics of interest to the Goddard GN&C engineering community. This helped foster better communications of some of the engineering efforts in the Branch. These seminars were generally presented by members of the FDAB and included the following:

- The Navigation Standards program (Felipe Flores-Amaya)
- TDRS Support of Spacecraft without TDRS Transponders (Greg Marr)
- Results of the TIMED Mishap Investigation Board (Steven Andrews)
- Balloon Arcsecond Pointer Feasibility Study (Keith DeWeese)
- The University Nanosat Program (Lucien Cox)
- Current Plans and Status of Formation Flying Activities at Goddard (Jesse Leitner)
- Professional Development Program Experiences (James O'Donnell)
- FKSI Trajectory Design (Greg Marr)

The seminar series also included a number of presentations from speakers outside of Goddard. This included presentations on the AutoFDS automated flight dynamics product generation software package, the use of Piograms for analysis (presented by Dr. Itzhack Bar-Itzhack of the Technion-Israel Institute of Technology), and solar flux prediction observations (presented by Dr. Kenneth Schatten of a.i.solutions, Inc. Following a break during the summer, the weekly seminars resumed in September and will continue through 2004.

[Technical contact: Thomas Stengle]

8.0 Outreach Activities

8.1 SAMPEX University Operations

The University of Maryland Aerospace Engineering Department completed its fourth full year of sole responsibility for flight dynamics support of the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) spacecraft. In this role, a team of University of Maryland undergraduate and graduate students provides routine spacecraft orbit determination, attitude determination, attitude sensor analysis, and flight dynamics product generation. This effort is sponsored and supported by the FDAB, which provides consultation support as needed and periodically reviews the overall program status. This has been a very successful outreach initiative and gives the student team practical experience and training in spacecraft flight dynamics computations, the use of several commercial ground support tools, and analysis of flight data. As an additional benefit, this program helps give students valuable experience for future employment.

[Technical Contact: Thomas Stengle]

8.2 TableSat

TableSat is an interactive, single axis hardware simulator that physically demonstrates the dynamics of attitude control systems. Using a simple radio communications (RF) link, the table is controlled by a laptop computer. A gyro package and set of fans are mounted on a 15 inch diameter table that rests on a centered pin. TableSat's hardware complement includes coarse sun sensors, a receiver, transmitter and batteries. The laptop, containing Simulink, is outfitted with a receiver and transmitter set. Simulink is a graphical controls and analysis tool. This system allows the user to 'fly' the table. Control systems can be modeled and modified in Simulink resulting in a real-time reaction of the table. The table was developed as a demonstration tool for the "Attitude Control Systems for Non-ACS Engineers" Course.

Due to the very positive feedback from the class participants, a storyboard was developed to create interest in attitude control systems at conferences and universities. The table electronics were repackaged with clear labels. The team used TableSat as part of the "Take Your Kids to Work Day" demonstrations. The demonstration covered basic concepts of stability and open versus closed-loop control. Other demonstrations have been given at the University of Florida, University of Maryland and at the GSFC Visitor Center.

To expand on the full potential of the TableSat concept, the TableSat Team is working with the University of Maryland to create a next generation demonstration tool. This modified TableSat will be capable of demonstrating the linear and non-linear properties that are typical for most spacecraft attitude control systems.

[Technical contact: David Mangus]

8.3 Visiting Student Enrichment Program (VSEP)

Mr. Eric Sampson, from University of Maryland, investigated and reported on the use of low thrust options for inclination changes in low Earth orbit for the repositioning of

NASA resources. Mr. Sampson performed analyses of several different low thrust systems, applied this research to high-fidelity numerical flight dynamics software, and reported on the results. This work is in addition to his other VSEP duties including poster sessions, final reports, and VSEP trips to other NASA centers.

[Technical contact: David Folta]

8.4 Graduate Student Research Program (GSRP)

Mr. Ryan Russell, from the University of Texas (UT) at Austin, investigated the use of Cycler Trajectory Design for both interplanetary mission design and applications to lunar missions. His Ph.D. research is being used by Code 595 for optimization of trajectories. He is also working on the UT program called Copernicus, developed by a previous GSRP student who is now a professor at UT. This program is useful in the total optimization of trajectories in any orbit regime. It is currently being used for support of a mission to Titan.

[Technical contact: David Folta]

8.5 Summer Intern Program

During the summer of 2003, FDAB personnel provided mentoring to Joni Jorgensen, an aerospace engineering student from the University of Kansas participating in the Summer Intern Program. Mr. Mesarch and Mr. Folta served as mentors to Miss Jorgensen in the area of trajectory design at the request of her primary mentor Dr. Ed Sittler of Code 692. Miss Jorgensen's task was to study the technical feasibility of obtaining greater science return through modifications to the baseline trajectory for the Solar Probe mission. The main purpose of the Solar Probe mission is to perform a very low perihelion (5 solar radii) pass providing the opportunity for in situ solar science capture. The Solar Probe mission will be using a high-energy transfer to achieve an encounter with Jupiter. The Jupiter gravity assist will enable the Solar Probe to raise its inclination to 90 degrees while lowering its perihelion to 5 solar radii.

Mr. Mesarch and Mr. Folta discussed the principles of designing missions utilizing gravity assists including the patched conic method with Miss Jorgensen. Miss Jorgensen's work included determining available launch days given the launch payload, picking a baseline launch case, and redesigning the trajectory to achieve the correct perihelion parameters. Following perihelion, the trajectory was changed using an impulsive (V maneuver to lower the orbit period, ensuring more perihelion passes over the length of the mission. Miss Jorgensen then used the (V numbers, the rocket equation, and thruster characteristics to estimate the propellant used and thruster firing durations. Miss Jorgensen learned to use Satellite Tool Kit's Astrogator module to perform much of this analysis.

[Technical contacts: Michael Mesarch & David Folta]

Appendix A – Goddard and NASA Awards

Team Awards

Langley Honor Award, Group Achievement Award, SAGE III Team: Lynch, Beckman, Toth

NASA Honor Award, Group Achievement Award, GSFC Data Systems Standards Team: Felipe Flores-Amaya.

NASA GSFC Annual Award 2003 for Advanced Attitude Determination and Sensor Calibration Technology Team (Thienel, Harman)

NASA GSFC Excellence Award 2003 for Far Ultraviolet Spectroscopic Explorer Attitude Control System Recovery Team (Thienel, Harman, Mangus)

NASA Group Achievement Award to the Microwave Anistotropy Probe (MAP) Team

NASA Group Achievement Award to the Microwave Anistotropy Probe (MAP) Guidance, Navigation and Control (GN&C) Team.

GSFC OBPR New Start Initiative Outstanding Teamwork - 10/22/03 (Carptenter, Vaughn, Petruzzo), In recognition of the team contributing responsively and substantially to the support of the OBPR FY03-1 Code U new initiative, thus enabling and contributing towards the future of the OBPR initiative.

Individual Awards

David C. Folta: Mentor Award (2003 NASA Academy). For contribution as a Mentor in the NASA Academy Program that provides for summer internships for graduate and post-doc level students to perform advanced research.

Marco A. Concha: Outstanding Mentor (2003 GSFC Awards of Excellence): In recognition of enthusiasm, positive attitude and great capability to teach and guide people from all levels of education and background.

Patent Submittals

Magnav/GPS patent application was submitted to the Patent Office.

David A. Quinn was issued US Patent #6,594,582 on July 15, 2003 for his invention entitled, "Compound Eye GPS Attitude and Navigation Sensor (CEGANS)".

The invention is a GPS system for navigation and attitude determination, comprising a sensor array including a convex hemispherical mounting structure having a plurality of mounting surfaces, and a plurality of antennas mounted to the mounting surfaces for receiving signals from space vehicles of a GPS constellation. The invention also includes a receiver for collecting the signals and making navigation and attitude determinations. In an alternate embodiment the present invention may include two opposing convex hemispherical mounting structures, each of the mounting structures having a plurality of mounting surfaces, and a plurality of antennas mounted to the mounting surfaces.

All the details are available on-line at:

http://patft.uspto.gov/netacgi/nph-Parser?Sect1=PTO2&Sect2=HITOFF&p=1&u=/netahtml/search-bool.html&r=1&f=G&l=50&co1=AND&d=ptxt&s1=APYMD-20000512&s2=Quinn.INZZ.&OS=APD/05-12-2000+AND+IN/Quinn&RS=APD/05-12-2000+AND+IN/Quinn

Appendix B – University Grants

The following cooperative agreements to conduct research in the area of Precise Relative Navigation for High Earth and Libration Point Missions was awarded under the NRA-03-GSFC/AETD-01, "Formation Navigation, Control, and Mission Design Algorithms." Awards started in July 2003 and are renewable for up to three years.

- GRANT NCC5-721 with **University of Colorado** (Penina Axelrad) titled "Assessment of Intersatellite Measurements for Precision Relative Navigation of HEO Satellite Formations."
- GRANT NCC5-722 with **Cornell University** (Mark Psiaki) titled "Relative Navigation of Formations of High-Earth-Orbiting Satellites Using Dual-Frequency Civilian GPS Technology."
- NCC5-723 with the **Univ. of Missouri** - Rolla, titled "Libration Point Mission Control"
- GRANT NCC5-732 with **University of Texas** (Glenn Lightsey) titled "Relative Orbit Determination for Multi-SC Libration Point Missions."
- GRANT NCC5-733 with **University of Texas** (Bob Bishop) titled "Autonomous Navigation for Libration Point Formation Flying Missions."
- GRANT NCC5-736 with **Texas A&M University** (Terry Alfriend) titled "Mitigation of the Impact of Sensing Noise on the Precise Formation Flying Control Problem."
- NCC5-737 with **Texas A&M**, titled"Modeling and Control of Libration Point Satellite Formations"
- NCC5-726 with **University of California, Los Angeles** (Jason Speyer) " Fault Detection, Identification, Reconstruction, and Fault-Tolerant Estimation for a Satellite and Satellite Cluster"
- NCC5-728 with **University of Cincinnati** (Trevor Williams and Gary Slater) "Collision Avoidance and Safe Mode for Satellite Formations"

Other grants under the direction of the branch include:

Purdue University, Dr. Howell: Grants were established to continue Dynamical Systems (DS) applications. Investigation involved further study of DS applications of manifolds, improvements to the Generator utility to include additional information on lunar gravity assist and targeting schemes, investigation of orbit bifurcation of manifolds, and investigation of the use of combinatorics for trajectory design and optimization. The results of this grant was used to design the trajectories of NGST, Triana, Constellation-X, FKSI, and others

Additionally Purdue researched the intersections of manifolds in the Earth-Moon to Sun-Earth Environments. This researched supports the "Lunar Gateway Technology" as envisioned by the Space Architects effort.

University of Illinois at Urbana Champaign, Dr. Coverstone and Dr. Prussing; Investigation and development of genetic algorithms and primer vector theory applications to optimization of orbit deign continued. The UIUC Computational Astrodynamic Research Laboratory (CARL) investigated orbital state transition matrix methods. Several established techniques have been identified. The varying strengths and weaknesses of the methods were established for Gim and Alfriend, Goodyear, Danby, and Battin, Matrix methods for the approximate solution of differential equations are applied to the development of general perturbations in rectangular coordinates. Results of this grant was used to minimze the DV and Fuel costs on SDO, GPM, and Leonardo.

Princeton University via Innovative Orbital Design, Dr. Belbruno; Investigation continued on using perturbation models of Quasi-Stationary Location in the Sun-Earth/Moon systems. Validation of Hills equations and the Circular and Elliptical Restricted Three body models were completed and the mathematical design was reviewed. . Results were verified using GSFC models and expertise. The control area was expanded to wider regions in the Sun-Earth libration Co-linear regions. These results were used future libration orbit missions.

Virginia Tech, Dr. Hall: Investigated a special class of coplanar time-optimal orbital maneuvers, in which the space-craft is controlled to move ahead of or behind its orbit position using a constant thrust whose direction is the control variable. The minimum-time, constant-thrust, orbit transfer problem is well established as one of the fundamental problems in control of spacecraft trajectories.

In this work, we consider the minimum-time orbital phasing maneuver using constant thrust with the thrust angle as the control variable. Specifically, we pose and obtain solutions to the problem of moving a point mass spacecraft from one point in a given circular orbit to a different point in the same orbit, differing only by a phase angle Á. This problem is of course the same as the same-orbit rendezvous problem. However, our motivation is not rendezvous, but rather the formation-establishment and formation-keeping maneuvers associated with formation flying missions. We want to compute minimum-time solutions for comparison with nonlinear feedback controllers designed to support such missions.

We define the idealized model and state the equations of motion, non-dimensionalizing the equations so that the dimensionless thrust, T, and the phase angle, Á, are the only parameters in the problem. We establish the minimum-time transfer problem, which leads to a two-point boundary value problem requiring the determination of the unknown initial conditions for the Lagrange multipliers or costates. We present some example solutions intended to illustrate a certain near-invariance principle that is found within the various families of solutions for varying thrust and phase angle. This near-invariance is the primary result of this work and should be useful in developing further results relevant to this problem. The figure illustrates this near-invariance, as the figure covers several orders of magnitude of the thrust, and essentially the entire range of phase angle of interest.

University of Cincinnati, Dr. Trevor Williams: Investigated the use of solar sail effects for both formation flying and orbit maintenance in various orbit regimes. This analysis was useful in address several mission concepts from MMS formation stability to the hovering of spacecraft at asteroids. Several papers and reports have been written and delivered throughout the year.

University of Maryland, College Park: NAG5-9890: For research entitled, “Rarefied Flow Aerodynamics and Control of Formation Flying Satellites. Principal Investigator: Dr. Mark J. Lewis.

Appendix C – SBIR Contracts

CONTRACT NAS5-02110 with **NAVSYS Corporation** titled "3D Antenna Array and GPS Receiver for Combined Navigation/Attitude Determination." The objective of this SBIR Phase II effort is to develop a Space-based Software GPS Receiver (SSGR), Engineering Development Unit. The SSGR is based on a digital multi-element phased array design that can be configured to provide: 4pi steridian field of view for all-around GPS satellite visibility; digital beam and null-forming to allow tracking of both high power and low power GPS satellites; attitude determination to allow operation on a spinning satellite; advanced signal processing to allow extremely low power GPS satellite signal detection; precision GPS navigation capability using WADGPS corrections; and integrated GPS orbit determination using NASA GSFC's GPS Enhanced Orbit Navigation Software (GEONS).

[Technical contact: Mike Moreau]

CONTRACT NAS5-03027 with **Princeton Satellite Systems** titled "A Reconfigurable, Decentralized Framework for Formation Flying Control."The proposed concept is a decentralized guidance and control system, organized in a multiple-team framework, and implemented within the Princeton Satellite Systems (PSS) ObjectAgent architecture. In the ObjectAgent architecture, Agents may be remotely added, removed or replaced post-launch to increase mission flexibility and robustness. This level of reconfigurability exceeds the state-of-the-art in traditional flight software. The reconfigurable, decentralized system will enable the number of spacecraft in the cluster to change post-launch, will be capable of supporting clusters with large numbers of satellites, and will allow significant software modifications to be made on-orbit in a robust manner.

[Technical contact: Russell Carpenter]

Appendix D – Conferences and Papers

Given below are abstracts from professional papers and technical presentations that were prepared and delivered in FY03 by branch members.

JOURNAL ARTICLES

Classical and Quantum Gravity, Vol. 20, No. 10, May 2003.

"Laser Interferometer Space Antenna Dynamics and Controls Model," Maghami, Hyde (GSFC)

ABSTRACT: A 19 degree-of-freedom (DOF) dynamics and controls model of a Laser Interferometer Space Antenna (LISA) spacecraft has been developed. This model is used to evaluate the feasibility of the dynamic pointing and positioning requirements of a typical LISA spacecraft. These requirements must be met for LISA to be able to successfully detect gravitational waves in the frequency band of interest (0.1-100 mHz). The 19-DOF model includes all rigid-body degrees of freedom. A number of disturbance sources, both internal and external, are included. Preliminary designs for the four control systems that comprise the LISA Disturbance Reduction System (DRS) have been completed and are included in the model. Simulation studies are performed to demonstrate that the LISA pointing and positioning requirements are feasible and can be met.

CONFERENCES

5th Int. ESA Conf. On Guidance, Navigation, and Control Systems, Frascati, Italy, October 2002.

"Controller Design for the ST7 Disturbance Reduction System, " Maghami, Markley, Dennehy, Houghton (GSFC), and Folkner (JPL)

ABSTRACT: The Space Technology 7 experiment will perform an on-orbit system-level validation of two specific Disturbance Reduction System technologies: a gravitational reference sensor employing a freefloating test mass and a set of micronewton colloidal thrusters. The Disturbance Reduction System is designed to maintain a spacecraft's position with respect to the free-floating test mass to less than 10 nm/vHz, over the frequency range 10-3 Hz to 10-2 Hz. This paper presents the design and analysis of the coupled drag-free and attitude control system that closes the loop between the gravitational reference sensor and the micronewton thrusters while incorporating star tracker data at low frequencies. The effects of actuation and measurement noise and disturbances on the spacecraft and test masses are evaluated in a seven degree- of-freedom planar model incorporating two translational and one rotational degrees of freedom for the spacecraft and two translational degrees of freedom for each test mass.

53rd International Astronautical Congress, The World Space Congress – 2002, Houston, TX, October 10-19, 2002

"Servicing And Deployment Of National Resources In Sun-Earth Libration Point Orbits," Folta, Beckman, Marr, Mesarch, Cooley, Leete (GSFC)

ABSTRACT: Spacecraft travel between the Sun-Earth system, the Earth-Moon system, and beyond has received extensive attention recently. The existence of a connection between unstable regions enables mission designers to envision scenarios of multiple spacecraft traveling cheaply from system to system, rendezvousing, servicing, and refueling along the way. This paper presents examples of transfers between the Sun-Earth and Earth-Moon systems using a true ephemeris and perturbation model. It shows the _V costs associated with these transfers, including the costs to reach the staging region from the Earth. It explores both impulsive and low thrust transfer trajectories. Additionally, analysis that looks specifically at the use of nuclear power in libration point orbits and the issues associated with them such as inadvertent Earth return is addressed. Statistical analysis of Earth returns and the design of biased orbits to prevent any possible return are discussed. Lastly, the idea of rendezvous between spacecraft in libration point orbits using impulsive maneuvers is addressed.

New Trends in Astrodynamics and Applications," College Park, Maryland, January 20-22, 2003.

"Formation Flying Design and Applications in Weak Stability Boundary Regions," Folta (GSFC)

ABSTRACT: Weak stability regions serve as superior locations for interferomertric scientific investigations. These regions are often selected to minimize environmental disturbances and maximize observing efficiency. Designs of formations in these regions are becoming ever more challenging as more complex missions are envisioned. The development of algorithms to enable the capability for formation design must be further enabled to incorporate better understanding of weak stability boundary solution space. This development will improve the efficiency and expand the capabilities of current approaches.

The Goddard Space Flight Center (GSFC) is currently supporting multiple formation missions in weak stability boundary regions. This end-to-end support consists of mission operations, trajectory design, and control. It also includes both algorithm and software development. The Constellation-X, Maxim, and Stellar Imager missions are examples of the use of improved numerical methods for attaining constrained formation geometries and controlling their dynamical evolution. This paper presents a survey of formation missions in the weak stability boundary regions and a brief description of formation design using numerical and dynamical techniques.

"A Nonlinear, Six-Degree Of Freedom, Precision Formation Control Algorithm, Based On Restricted Three Body Dynamics," Luquette (GSFC) and Sanner (Univ. of Maryland)

ABSTRACT: Precision Formation Flying is an enabling technology for a variety of proposed space-based observatories, including the Micro-Arcsecond X-ray Imaging Mission (MAXIM), the associated MAXIM pathfinder mission, Stellar Imager and the Terrestrial Planet Finder (TPF). An essential element of the technology is the control algorithm. This paper discusses the development of a nonlinear, six-degree of freedom (6DOF) control algorithm for maintaining the relative position and attitude of a spacecraft within a formation. The translation dynamics are based on the equations of

motion for the general restricted three body problem. The control law guarantees the tracking error convergences to zero, based on a Lyapunov analysis. The simulation, modeled after the MAXIM Pathfinder mission, maintains the relative position and attitude of a Follower spacecraft with respect to a Leader spacecraft, stationed near the L2 libration point in the Sun-Earth system.

AAS Guidance and Control Conference, Breckenridge, CO, Feb. 5-9, 2003

"A Nonlinear Observer for Gyro Alignment Estimation", Thienel (GSFC), Sanner (Univ. MD)

ABSTRACT: A nonlinear observer for gyro alignment estimation is presented. The observer is composed of two error terms, namely an attitude error and an alignment error. The observer is globally stable with exponential convergence of the attitude errors. The gyro alignment estimate converges to the true alignment when the system is completely observable.

"First Results from a Hardware-in-the-Loop Demonstration of Closed-Loop Autonomous Formation Flying," Gill (DLR), Naasz (GSFC), Ebinuma (Univ. Texas at Austin)

ABSTRACT: A closed-loop system for the demonstration of autonomous satellite formation flying technologies using hardware-in-the-loop has been developed. Making use of a GPS signal simulator with a dual radio frequency outlet, the system includes two GPS space receivers as well as a powerful onboard navigation processor dedicated to the GPS-based guidance, navigation, and control of a satellite formation in real-time. The closed-loop system allows realistic simulations of autonomous formation flying scenarios, enabling research in the fields of tracking and orbit control strategies for a wide range of applications

The autonomous closed-loop formation acquisition and keeping strategy is based on Lyapunovs direct control method as applied to the standard set of Keplerian elements. This approach not only assures global and asymptotic stability of the control but also maintains valuable physical insight into the applied control vectors. Furthermore, the approach can account for system uncertainties and effectively avoids a computationally expensive solution of the two point boundary problem, which renders the concept particularly attractive for implementation in onboard processors.

A guidance law has been developed which strictly separates the relative from the absolute motion, thus avoiding the numerical integration of a target trajectory in the onboard processor. Moreover, upon using precise kinematic relative GPS solutions, a dynamical modeling or filtering is avoided which provides for an efficient implementation of the process on an onboard processor. A sample formation flying scenario has been created aiming at the autonomous transition of a Low Earth Orbit satellite formation from an initial along-track separation of 800 m to a target distance of 100 m. Assuming a low-thrust actuator which may be accommodated on a small satellite, a typical control accuracy of less than 5 m has been achieved which proves the applicability of autonomous formation flying techniques to formations of satellites as close as 50 m.

"Precision Pointing for the Laser Interferometer Space Antenna Mission," Maghami, Hyde (GSFC)

ABSTRACT: The Laser Interferometer Space Antenna (LISA) mission is a planned NASA-ESA gravitational wave detector consisting of three spacecraft in heliocentric orbit. Lasers are used to measure distance fluctuations between proof masses aboard each spacecraft to the picometer level over a 5 million kilometer separation. Each spacecraft and its two laser transmit/receive telescopes must be held stable in pointing to less than 8 nanoradians per root Hertz in the frequency band 1-100 mHz. The pointing error is sensed in the received beam and the spacecraft attitude is controlled with a set of micro-Newton thrusters. Requirements, sensors, actuators, control design, and simulations are described.

"Design and Analysis of the ST7 Disturbance Reduction System (DRS) Spacecraft Controller," Maghami, Markley, Houghton, Dennehy (GSFC)

ABSTRACT: The Space Technology 7 experiment will perform an on-orbit system-level validation of two specific Disturbance Reduction System technologies: a gravitational reference sensor employing a free-floating test mass and a set of micronewton colloidal thrusters. The Disturbance Reduction System is designed to maintain a spacecraft's position with respect to the free-floating test mass to less than 10 nm/vHz, over the frequency range 10-3 Hz to 10-2 Hz. This paper presents the design and analysis of the coupled drag-free and attitude control system that closes the loop between the gravitational reference sensor and the micronewton thrusters while incorporating star tracker data at low frequencies. The effects of actuation and measurement noise and disturbances on the spacecraft and test masses are evaluated in a seven-degree-of-freedom planar model incorporating two translational and one rotational degrees of freedom for the spacecraft and two translational degrees of freedom for each test mass.

AAS/AIAA Space Flight Mechanics Meeting, Ponce, Puerto Rico, Feb. 9-13, 2003.

"Integrated Orbit and Attitude Control for a Nanosatellite with Power Constraints," Naasz (GSFC), Berry, Kim, and Hall (Va. Tech)

ABSTRACT: Small satellites tend to be power-limited, so that actuators used to control the orbit and attitude must compete with each other as well as with other subsystems for limited electrical power. The Virginia Tech nanosatellite project, HokieSat, must use its limited power resources to operate pulsed-plasma thrusters for orbit control and magnetic torque coils for attitude control, while also providing power to a GPS receiver, a crosslink transceiver, and other subsystems. The orbit and attitude control strategies were developed independently. The attitude control system is based on an application of LQR to an averaged system of equations, whereas the orbit control is based on orbit element feedback. In this paper we describe the strategy for integrating these two control systems and present simulation results to verify the strategy.

"Orbit Determination Support for the Microwave Anisotropy Probe (MAP)," Son H. Truong (GSFC), Osvaldo O. Cuevas (GSFC), and Steven Slojkowski (CSC)

ABSTRACT: NASA's Microwave Anisotropy Probe (MAP) was launched from the Cape Canaveral Air Force Station Complex 17 aboard a Delta II 7425-10 expendable launch vehicle on June 30, 2001. The spacecraft received a nominal direct insertion by the Delta expendable launch vehicle into a 185-km circular orbit with a 28.7° inclination. MAP was then maneuvered into a sequence of phasing loops designed to set up a lunar swingby (gravity-assisted acceleration) of the spacecraft onto a transfer trajectory to a lissajous orbit about the Earth-Sun L2 Lagrange point, about 1.5 million km from Earth. Because of its complex orbital characteristics, the mission provided a unique challenge for orbit determination (OD) support in many orbital regimes. This paper summarizes the premission trajectory covariance error analysis, as well as actual OD results. The use and impact of the various tracking stations, systems, and measurements are also discussed. Important lessons learned from the MAP OD support team are presented. There is a discussion of the challenges presented to OD support including the effects of delta-Vs at apogee as well as perigee, and the impact of the spacecraft attitude mode on the OD accuracy and covariance analysis.

Third International Workshop on Satellite Constellations and Formation Flying, Pisa, Italy, February 24-26, 2003

"The Magnetospheric Multi-Scale Mission: An Electronically Tethered Constellation of Four Spacecraft," Curtis, Petruzzo, Peterson (GSFC), Clark (EER)

ABSTRACT: The Magnetospheric Multi-Scale (MMS) mission is part of NASA's Solar Terrestrial Physics Probe line. Its goal is to understand the fundamental physics which underlies the solar terrestrial environment and which drives space weather. MMS is a fully funded mission with a launch planned in 2009. It is composed of four identical spacecraft, each having a complete set of particles and fields instruments to study the ambient plasma. The spacecraft fly in a tetrahedral array with inter-spacecraft separations ranging for 10 to 1000's of kilometers in four distinct highly eccentric orbital phases. The complete mission is tightly choreographed to be executed within a two-year period to help contain mission costs in the relatively high radiation environment. These orbit phases combine to give a grand tour of Earth's space environment. The spacecraft will have an intercommunication capability and also an inter-ranging capability along with a robust onboard propulsion capability. Discussed here, from the viewpoint of the science objectives that drive the mission, are the options being considered for the inter-spacecraft separation measurement. Also discussed are the separation strategies and how the natural evolution of the tetrahedral formation over a number of orbits can be exploited to achieve intermediate spacecraft separations without the expenditure of the limited fuel supplies.

AIAA/AAS Astrodynamics Specialist Conference, Big Sky, Montana August 2003

"Global Precipitation Measurement (GPM) Orbit Design And Autonomous Maneuvers," Folta, Mendelsohn (GSFC), Mailhe (ai-solutions)

ABSTRACT: The NASA Goddard Space Flight Center's Global Precipitation Measurement (GPM) mission must meet the challenge of measuring worldwide precipitation every three hours. The GPM core spacecraft, part of a constellation, will be required to maintain a circular orbit in a high drag environment at a near-critical inclination. Analysis shows that a mean orbit altitude of 407 km is necessary to prevent ground track repeating. Combined with goals to minimize maneuver operation impacts to science data collection and to enable reasonable long-term orbit predictions, the GPM project has decided to fly the GSFC autonomous maneuver system, AutoCon™. This system is a follow-up version of the highly successful New Millennium Program technology flown onboard the Earth Observing-1 formation flying mission.

This paper presents the driving science requirements and goals of the GPM mission and shows how they will be met. Selection of the mean semi-major axis, eccentricity, and the ΔV budget for several ballistic properties are presented. The architecture of the autonomous maneuvering system to meet the goals and requirements is presented along with simulations using GPM parameters. Additionally, the use of the GPM autonomous system to mitigate possible collision avoidance and to aid other spacecraft systems during navigation outages is explored.

"Testing of Gyroless Estimation Algorithms for the FUSE Spacecraft," Harman, Thienel (GSFC), Oshman (Technion Institute of Technology)

ABSTRACT: The Far Ultraviolet Spectroscopic Explorer (FUSE) is equipped with two ring laser gyros on each of the spacecraft body axes. In May 2001 one gyro failed. It is anticipated that all of the remaining gyros will also fail, based on intensity warnings. In addition to the gyro failure, two of four reaction wheels failed in late 2001. The spacecraft control now relies heavily on magnetic torque to perform the necessary science maneuvers and hold on target. The only sensor consistently available during slews is a magnetometer. This paper documents the testing and development of magnetometer-based gyroless attitude and rate estimation algorithms for FUSE. The results of two approaches are presented, one relies on a kinematic model for propagation, a method used in aircraft tracking, and the other is a pseudo-linear Kalman filter that utilizes Euler's equations in the propagation of the estimated rate. Both algorithms are tested using flight data collected over a few months after the reaction wheel failure. Finally, the question of closed-loop stability is addressed. The ability of the controller to meet the science slew requirements, without the gyros, is analyzed.

"18-Degree-of-Freedom Controller Design for the ST7 Disturbance Reduction," Markley, Maghami, Houghton, Hsu (GSFC)

ABSTRACT: The Space Technology 7 experiment will perform an on-orbit system-level validation of a Disturbance Reduction System employing gravitational reference sensors and micronewton colloidal thrusters to maintain a spacecraft's position with respect to free-floating test masses in the gravitational reference sensors to less than 10 nm/vHz over the frequency range 1 to 30 mHz. This paper presents the design and analysis of the control system that closes the loop between the gravitational reference sensors and the micronewton thrusters while incorporating star tracker data at low frequencies. The effects of disturbances and actuation and measurement noise are evaluated in a eighteen-degree-of-freedom model.

International Symposium on Formation Flying Missions & Technologies, Toulouse, France

"NASA's Autonomous Formation Flying Technology Demonstration, Earth Observing-1 (EO-1)," Folta, Bristow (GSFC), Hawkins, Dell (ai-solutions)

ABSTRACT: NASA's first autonomous formation flying mission, the New Millennium Program's (NMP) Earth Observing-1 (EO-1) spacecraft, recently completed its principal goal of demonstrating advanced formation control technology. This paper provides an overview of the evolution of an onboard system that was developed originally as a ground mission planning and operations tool. We discuss the Goddard Space Flight Center's formation flying algorithm, the onboard flight design and its implementation, the interface and functionality of the onboard system, and the implementation of a Kalman filter based GPS data smoother. A number of safeguards that allow the incremental phasing in of autonomy and alleviate the potential for mission-impacting anomalies from the on-board autonomous system are discussed. A comparison of the maneuvers planned onboard using the EO-1 autonomous control system to those from the operational ground-based maneuver planning system is presented to quantify our success. The maneuvers discussed encompass reactionary and routine formation maintenance. Definitive orbital data is presented that verifies all formation flying requirements.

AIAA Guidance, Navigation and Control Conference in Austin, TX, August 11-14.

"Evaluation of a Drag-Free Control Concept for Missions in Low Earth Orbit," Fleck, Starin (GSFC)

ABSTRACT: Atmospheric drag causes the greatest uncertainty in the equations of motion for spacecraft in Low Earth Orbit (LEO). If atmospheric drag effects can be continuously and autonomously counteracted through the use of a drag-free control system, drag may essentially be eliminated from the equations of motion for the spacecraft. The main perturbations on the spacecraft will then be those due to the gravitational field, which are much more easily predicted. Through dynamical analysis and numerical simulation, this paper presents some potential costs and benefits associated with the fuel used during continuous drag compensation. In light of this cost-benefit analysis, simulation results are used to validate the concept of drag-free control for LEO spacecraft missions having certain characteristics.

"Benchmark Problems For Spacecraft Formation Flying Missions," Carpenter, Leitner, Folta, Burns (GSFC)

ABSTRACT: To provide high-level focus to distributed space system flight dynamics and control research, several benchmark problems are suggested. These problems are not specific to any current or proposed mission, but instead are intended to capture high-level features that would be generic to many similar missions.

"Navigation Accuracy Guidelines For Orbital Formation Flying," Carpenter (GSFC), Alfriend (Texas A&M)

ABSTRACT: Some simple guidelines based on the accuracy in determining a satellite formation's semi-major axis differences are useful in making preliminary assessments of the navigation accuracy needed to support such missions. These guidelines are valid for any elliptical orbit, regardless of eccentricity. Although maneuvers required for formation establishment, reconfiguration, and station-keeping require accurate prediction of the state estimate to the maneuver time, and hence are directly affected by errors in all the orbital elements, experience has shown that determination of orbit plane orientation and orbit shape to acceptable levels is less challenging than the determination of orbital period or semi-major axis. Furthermore, any differences among the member's semi-major axes are undesirable for a satellite formation, since it will lead to differential along-track drift due to period differences. Since inevitable navigation errors prevent these differences from ever being zero, one may use the guidelines this paper presents to determine how much drift will result from a given relative navigation accuracy, or conversely what navigation accuracy is required to limit drift to a given rate. Since the guidelines do not account for non-two-body perturbations, they may be viewed as useful preliminary design tools, rather than as the basis for mission navigation requirements, which should be based on detailed analysis of the mission configuration, including all relevant sources of uncertainty.

Appendix E – Acronyms and Abbreviations

This appendix gives the definitions of acronyms used in this document.

AAS	American Astronautical Society
ACE	Attitude Control Electronics
ACS	Attitude Control System
ADS	Attitude Determination System
AE	Atmospheric Explorer
AETD	Applied Engineering and Technology Directorate
AGI	Analytical Graphics, Inc.
AIAA	American Institute of Aeronautics and Astronautics
ANTS	Autonomous Nano Technology Swarm
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
APS	Active Pixel Sensor
AUTOFDS	Autonomous Flight Dynamics System
BET	Best Estimate of Trajectory
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CANDOS	Communications and Navigation Demonstration on Shuttle
CAPS	Climate Change Research Initiative Aerosol Polarimetry Sensor
CCS	Constellation Coordination System
CCS	Cross-link Channel Simulator
CCD	Charge Coupled Device
CCDST	Charge Coupled Device Star Tracker
CCSDS	Consultative Committee for Space Data Systems
Cd	Coefficient of Drag
CEGANS	Compound Eye GPS Attitude and Navigation Sensor
CelNav	Celestial Navigation
CNES	Centre National d'Etudes Spatiales
CONTOUR	Comet Nucleus Tour
Con-X	Constellation X
Co-op	Cooperative Education
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CSC	Computer Sciences Corporation
CSOC	Consolidated Space Operations Contract
DFC	Drag Free Control
DMR	Detailed Mission Requirements
DOF	Degree of Freedom
DOWD	Differenced One-Way Doppler
DRS	Disturbance Reduction System
DC	Differential Correction
DCS	Dynamics Control System
DRO	Distant Retrograde Orbit
DSC	Deep Space Calibration
DSN	Deep Space Network

DSS	Distributed Space System
DSS	Digital Sun Sensor
DSSC	Data Standards Steering Council
DST	Dynamical Systems Theory
EFF	Enhanced Formation Flying
EKF	Extended Kalman Filter
EO	Earth Observing
EOS	Earth Observing System
ERBS	Earth Radiation Budget Satellite
ESA	European Space Agency
ESE	Earth Science Enterprise
ESMO	Earth Science Mission Operations
ESSP	Earth System Science Program
ESTO	Earth Science Technology Office
FD	Flight Dynamics
FDAB	Flight Dynamics Analysis Branch
FDF	Flight Dynamics Facility
FDS	Flight Dynamics System
FDT	Flight Dynamics Team
FFTB	Formation Flying Test Bed
FGS	Fine Guidance Sensor
FKSI	Fourier Kelvin Stellar Interferometer
FOR	Field of Regard
FOT	Flight Operations Team
FSS	Fine Sun Sensor
FSW	Flight Software
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	Fiscal Year
GEC	Geospace Electrodynamic Connections
GEO	Geosynchronous Earth Orbit
GEODE	GPS Enhanced Orbit Determination Experiment
GEONS	GPS-Enhanced Orbit Navigation System
GLAST	Gamma Ray Large Area Space Telescope
GMAN	General Maneuver
GMAT	Goddard Mission Analysis Tool
GMSEC	Goddard Mission Services Evolution Center
GN&C	Guidance, Navigation and Control
GNC	Guidance, Navigation and Control
GNCD	Guidance, Navigation, and Control Division
GOES	Geostationary Operational Environmental Satellite
GOTS	Government Off-The-Shelf
GPM	Global Precipitation Mission
GPMC	Goddard Program Management Council
GPS	Global Positioning Satellite
GRC	Glenn Research Center
GRS	Gravity Reference Sensor

GSFC	Goddard Space Flight Center
GSOC	German Space Operations Center
GSRP	Graduate Student Research Program
GTAS	General Trending and Analysis System
GTDS	Goddard Trajectory Determination System
GTO	Geostationary Transfer Orbit
GUI	Graphics User Interface
GUS	Gyroscopic Upper Stage
H	Momentum
HEO	High Earth Orbit/ Highly Elliptical Orbit
HGA	High Gain Antenna
HiFi	High Fidelity
HIRDLS	High Resolution Dynamic Limb Sounder
HIRP	Hybrid Integrated Rate Parameters
HRG	Hemispherical Resonator Gyro
HST	Hubble Space Telescope
HTML	HyperText Markup Language
I&T	Integration and Test
ICD	Interface Control Document
IMDC	Integrated Mission Design Center
IMU	Inertial Measurement Unit
InFocus	International Focusing Optics Collaboration for (Crab Sensitivity
ISS	International Space Station
IT	Ionosphere-Thermosphere
ITAR	International Traffic In Arms Regulation
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JWST	James Webb Space Telescope
Kbps	Kilobits per second
LaRC	Langley Research Center
LEO	Low Earth Orbit
LISA	Laser Interferometric Space Antenna
LoFi	Low Fidelity
LPT	Low Power Transceiver
LQG	Linear Quadratic Gaussian
LSE	Lunar Science Explorer
MAB	Mission Applications Branch
MAGNAV	Magnetometer Navigation
MAXIM	Micro-Arcsecond X-ray Imaging Mission
MC	Master Catalog
MCC	Mid Course Correction
MDR	Mission Design Requirements
MESA	Mission Engineering and System Analysis
Mi	Instrumental Magnitude
MIB	Mishap Investigation Board
MIDEX	Medium Explorer

MIT	Massachusetts Institute of Technology
M-J2000	Mean of J2000
MLS	Microwave Limb Sounder
MLS	Mean Local Solar
MLT	Mean Local Time
MMS	Magnetic Multi-scale Mission
MMS	Multi-Mission Spacecraft
MMSCAT	Multi-Mission Star Catalog
mN	micro-Newtons
MOC	Mission Operations Center
MoD	Mean of Date
MODIS	Moderate Resolution Imaging Spectroradiometer
MOMS	Mission Operations and Mission Services
MOR	Mission Operations Review
MOST	Mission Operations Support Team
MSASS	Multi-mission Single-Axis Stabilized Spacecraft
MSFC	Marshall Space Flight Center
MTASS	Multi-mission Three Axis Stabilized Spacecraft
Mv	Visual Magnitude
NASA	National Aeronautical and Space Administration
NET	No Earlier Than
NGST	Northrup-Grumman Space Technologies
NMP	New Millennium Program
NOAA	National Oceanic and Atmospherics Administration
NRL	Naval Research Laboratory
OBPR	Office of Biological and Physical Research
OBC	On-Board Computer
OCO	Orbiting Carbon Observatory
OMI	Ozone Monitoring Instrument
OSC	Orbital Sciences Corporation
OD	Orbit Determination
ODM	Orbit Data Message
PD	Proportional Derivative
PDP	Professional Development Program
PDR	Preliminary Design Review
PI	Principal Investigator
PIP	Professional Intern Program
PM	Proof Mass
PSI	Payload Systems, Inc.
PSD	Power Spectral Density
R&D	Research and Development
RASC	Revolutionary Aerospace Systems Concepts
Re	Earth Radii
RF	Radio Frequency
RFO	Request for Offer
RFI	Radio Frequency Interference

RLP	Rotating Libration Point
RMS	Root-Mean-Square
RSDO	Rapid Spacecraft Development Office
RSU	Rate Sensing Units
RTADS	Real Time Attitude Determination System
RTODS	Real-Time Orbit Determination System
RXTE	Rossi X-Ray Timing Explorer
SAA	South Atlantic Anomaly
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SANA	Space Assigned Numbers Authority
SBIR	Small Business Innovative Research
SCR	System Concept Review
SDO	Solar Dynamics Observatory
SDT	Satellite Dynamics Tool
SEU	Single Event Upset
SIRA	Solar Imaging Radio Array
SK	Stationkeeping
SLE	Space Link Extension
SM	Servicing Mission
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SPAD	Solar Pressure and Aerodynamic Drag
SPECS	Sub-millimeter Probe of the Evolution of Cosmic Structure
SPHERES	Synchronized Position Hold Engage Re-orient Experimental Satellites
SPM	Sun Point Mode
SPS	Standard Positioning Service
SRR	System Requirements Review
ST	Space Technology
ST	Star Tracker
STDT	Science and Technology Definition Team
STEREO	Solar-Terrestrial Relations Observatory
STK	Satellite Tool Kit
TAM	Three Axis Magnetometer
TCO	Technology Commercialization Office
TDRSS	Tracking Data Relay Satellite System
TES	Tropospheric Emission Spectrometer
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
TPF	Terrestrial Planet Finder
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TTI	Transfer Trajectory Injection
UARS	Upper Atmospheric Research Satellite
URL	Uniform Resource Locator
USGS	United States Geological Survey
USN	Universal Space Network

VAL	Virtual Almanac Library
VESPER	Venus Sounder for Planetary Exploration
VO	Visualization Option
VSEP	Visiting Student Enrichment Program
WIRE	Wide-Field Infrared Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
WRS	World Reference System
WSB	Weak Stability Boundary
WWW	World Wide Web
XML	Extensible Markup Language
XRSN	Transponder Remote Services Node

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 595, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2003. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including spacecraft navigation (autonomous and ground based), spacecraft trajectory design and maneuver planning, attitude analysis, attitude determination and sensor calibration, and attitude control subsystem (ACS) analysis and design. The FDAB currently provides support for missions and technology development projects involving NASA, other government agencies, academia, and private industry.

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